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Methods Development for Quantification of Ozone and Ozone Precursor Transport in California

CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY

AIR RESOURCES BOARD
Research Division

METHODS DEVELOPMENT FOR QUANTIFICATION OF OZONE AND OZONE PRECURSOR TRANSPORT IN CALIFORNIA

Final Report

Contract No. A932-143

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ABSTRACT

This project addresses the California Clean Air Act requirement to assess the relative contribution of upwind pollutants to violations of the state ozone standard in downwind areas. The objectives of the project were:

- To develop data analysis methods to quantify the contribution of upwind emissions to downwind ozone concentrations;
- To apply those methods to the transport of pollutants from the San Francisco Bay Area and the San Joaquin Valley Air Basins, plus the Lower Sacramento Valley, to receptor sites in the Upper Sacramento Valley; and
- To recommend the best methods to use for the Upper Sacramento Valley.

The project results should improve future analysis, modeling, and emission control efforts.

This project has included a number of tasks; such as preliminary planning, a field measurement study, and subsequent data analyses. A number of reports have documented the data collected during the field study. This report covers the data analysis portion of the project and includes information on important issues when considering pollutant transport, a discussion of the data analysis methods used in this project including the method limitations, a presentation of the results of applying the various methods, comparisons and evaluations of the results, and a discussion of project conclusions and of recommendations for future applications.

The data analysis methods which could be applied in future applications for the Upper Sac include transport paths and precursor contribution estimates using surface and aloft trajectories, 2-D pollutant flux estimates, ozone/tracer regressions, and analyses of unique signatures of VOC species and tracers of opportunity. In addition, air flow patterns should be characterized as a basis for any of the other methods. At least two of the methods should be applied at the same time, in order to strengthen the results. For future applications, the following recommendations are made:

- If limited to the use of existing monitoring, then only one method that we studied is possible: precursor contribution estimates for NO_x and ROG using surface trajectories. This method is only applicable to those Upper Sac receptors which are influenced by same-day surface transport.

- New hourly VOC-speciation monitoring will be needed in the Sacramento area to meet EPA's PAMS (Photochemical Assessment Monitoring Stations) requirements. If a similar monitor is also installed at one or more Upper Sac receptors, then VOC-signature analyses could be performed to quantify precursor transport. This technique enables the potential identification of the source of the air parcel based on the VOC signature if these signatures are observed to differ amoung source regions.

- Based on analyses in this study, if additional measurements can be taken such that 2-D flux plane and VOC-signature analysis methods can be employed, the combination of these techniques provides the most reliable quantification of ozone and ozone precursors. (Intensive field measurements on potential transport days would be required.) These methods are reliable because they are based on calculations and comparisons using physical parameters such as wind speed, wind direction, ozone concentration, and VOC speciation rather than relying on purely statistically related parameters which may not be physically related such as the timing of ozone peaks.

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DISCLAIMER

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1. INTRODUCTION

1.1 PROJECT RATIONALE AND OBJECTIVES

The State of California has been divided into 14 air basins. Air pollution control districts or air quality management districts in each basin have been concerned with the control of local emissions and the impact of those emissions on pollutant concentrations in their basin. Although many of the basin boundaries were established with terrain features in mind, prevailing wind patterns in the state still transport pollutants from one basin to another. This effect has been clearly demonstrated on a number of occasions through the use of tracer releases (see, for example: Smith et al., 1977; Lehrman et al., 1981; Smith and Shair, 1983; and Reible et al., 1982). Depending on the particular scenario, effective control strategies may require emission controls in the upwind air basin, the downwind air basin, or both.

The California Clean Air Act requires the California Air Resources Board (ARB) to assess the relative contribution of upwind pollutants to violations of the state ozone standard in the downwind areas. Past transport studies in California have documented pollutant transport on specific days, but have not always quantified the contribution of transported pollutants to ozone violations in the downwind area.

Grid modeling may ultimately be needed in many situations to evaluate the relative effects of different control strategies. However, many of the interbasin transport problems in the state involve complex flow patterns with strong terrain influences which are difficult and expensive to model. Limited upper-air meteorological and air quality data in many areas generally restrict the evaluation, and thus the effective use, of grid models. In addition, interbasin transport between some of the air basins does not result in significant receptor impact and thus should not receive the detailed treatment afforded by grid modeling.

This project was designed to develop and apply data analysis methods to quantify the contribution of transported pollutants to ozone violations in the Upper Sacramento Valley (Upper Sac), to evaluate the results of applying the various methods, and to recommend the best methods to use for the Upper Sac. The project results should improve future analysis, modeling, and control efforts.

The objectives of the project were:

- To develop data analysis methods to quantify the contribution of upwind emissions to downwind ozone concentrations;
- To apply those methods to the transport of pollutants from the San Francisco Bay Area (SF Bay Area) and the San Joaquin Valley Air Basins, plus the Lower Sacramento Valley (Broader Sac), to receptor sites in the Upper Sac; and
- To recommend the best methods to use for the Upper Sac receptor area.

During the period when this project was planned and carried out, the Upper Sac area was defined as the counties of Shasta, Tehama, Glenn, Butte, and Colusa. The upwind areas which might contribute transported pollutants to the Upper Sac area are the SF Bay Area, the San Joaquin Valley Air Basin (SJVAB), and the Broader Sac. Figure 1-1 is a map of the general area which shows these three areas. Note that if pollutants are transported from the SF Bay Area or from the SJVAB to the Upper Sac, they must first pass through the Broader Sac. The natural geographical/meteorological division between the Broader Sac and the Upper Sac is on an east/west line at Sutter Buttes.

In September 1992, the ARB modified the boundaries of the Upper Sac and Broader Sac areas (see Figure 1-2). These changes essentially moved the Broader Sac/Upper Sac boundary about 40 km south and added Yuba City and Marysville to the Upper Sac. These changes do not match the natural geographical/meteorological division between the two areas. Future transport assessments would require measurements at different locations than those used in this project.

This project has included a number of tasks, including preliminary planning, a field measurement study, and subsequent data analyses. A number of previous reports have documented the data collected during the field study (see Section 2 for a summary of the field study and associated references). This report covers the data analysis portion of the project, and includes information on important issues when considering pollutant transport, a discussion of the data analysis methods used in this project, a presentation of the results of applying the various methods, comparisons and evaluations of the results, and a discussion of project conclusions and of recommendations for future applications.

While we were performing work for this project, we were also performing work on another project on pollutant transport for the ARB ("A Study to Determine the Nature and Extent of Ozone and Ozone Precursor Transport in Selected Areas of California," Roberts et al., 1992). Since pollutant transport to the Upper Sac was one of the four areas selected for study during that parallel project, there was some overlap between the two projects. Results of some of the work performed for the current study was included in the earlier report, as well as in this one, in order to present the results to the ARB as soon as possible. This overlap occurs mainly in the estimation of precursor contribution estimates (see Section 6).

The rest of this section presents our technical approach, a summary of the project results, and our recommendations for future use of the methods applied during this project.

1.2 TECHNICAL APPROACH

A number of issues influenced our technical approach to quantifying pollutant transport, including the following. The impact of pollutant transport on the ozone air quality in a downwind basin is a function of the precursor emissions in the upwind basin, the losses of pollutants by deposition and reaction along the transport path, the formation of ozone along the transport path, the meteorological situation which transports and mixes

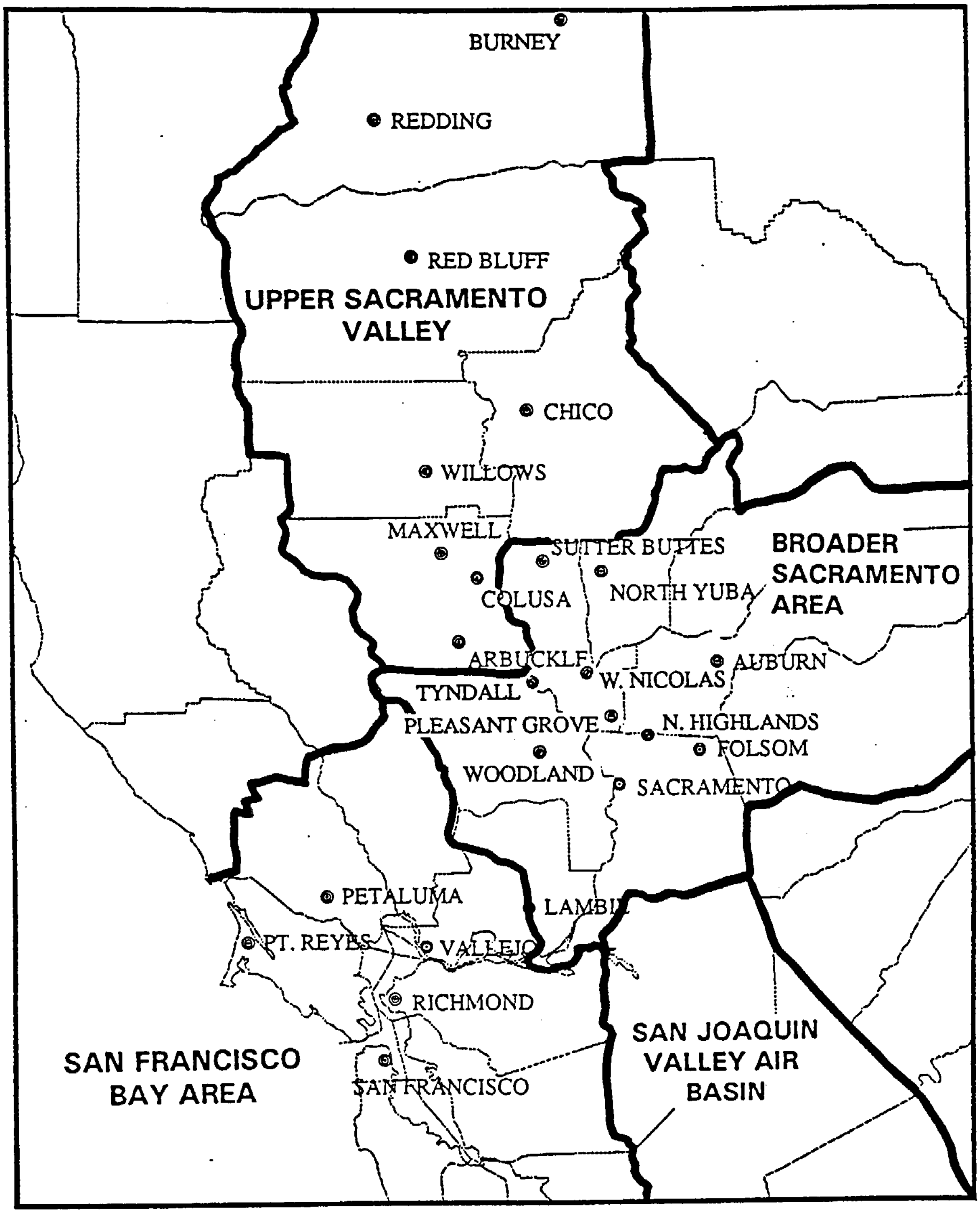


Figure 1-1. Map of Northern California showing the Upper Sacramento Valley, the Broader Sacramento Area (prior to September 1992), the San Francisco Bay Area, and selected sampling sites. All sites are shown in Figure 6-1 and listed with UTM coordinates in Appendix B.

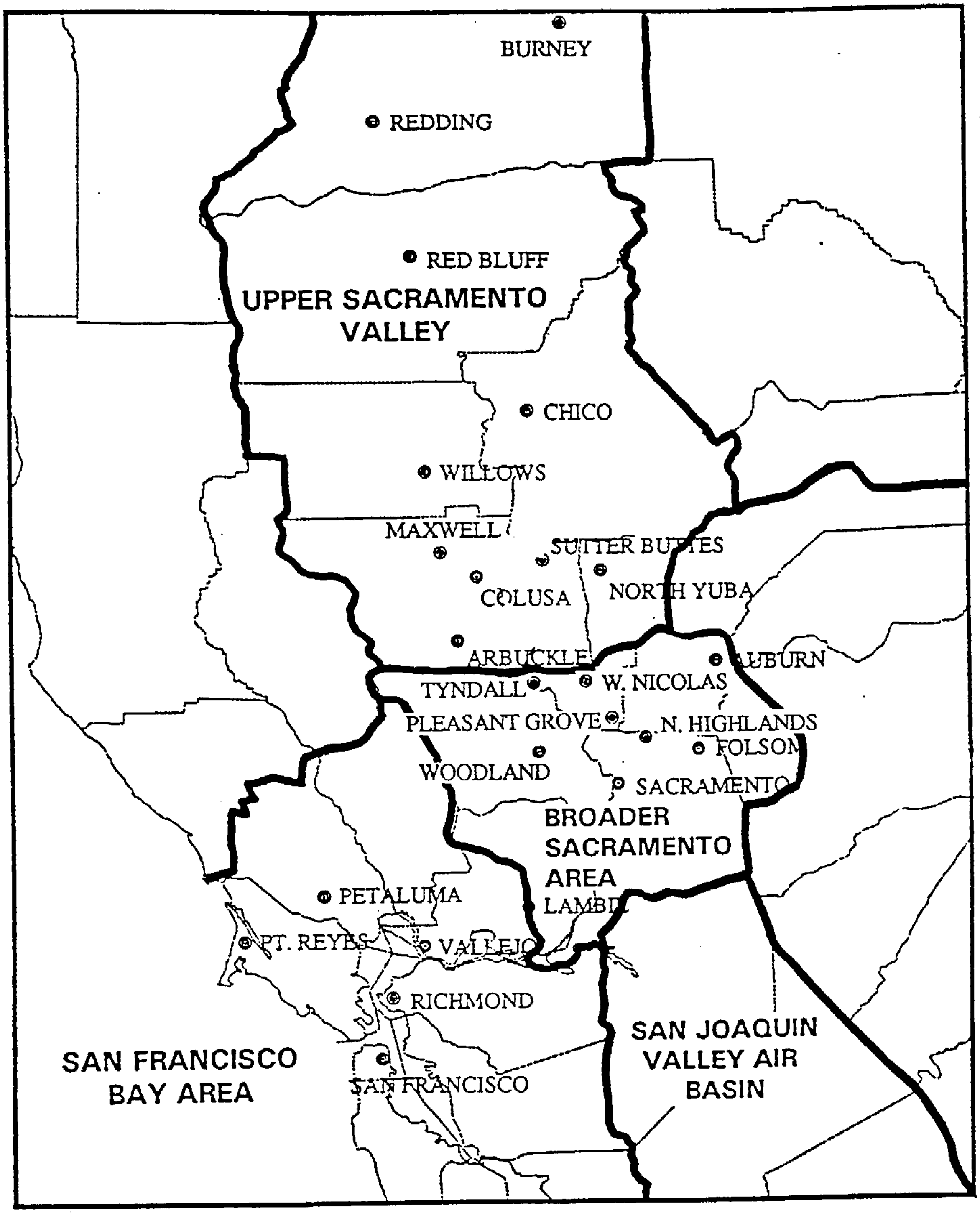


Figure 1-2. Map of Northern California showing the Upper Sacramento Valley, the Broader Sacramento Area (after September 1992), the San Francisco Bay Area, and selected sampling sites. All sites are shown in Figure 6-1 and listed with UTM coordinates in Appendix B.

the pollutants, and the local precursor emissions in the downwind basin. The geography of the region often influences the potential transport between air basins and the transport path. In addition, the availability of surface and aloft meteorological and air quality data will determine which potential data analysis methods could be applied to quantify pollutant transport to a downwind air basin.

To meet the project objectives, modeling or data analysis methods could be applied. For this project, we applied data analysis methods using meteorological and air quality data collected routinely or during special studies. The issues mentioned above lead us to design a technical approach which relied on developing multiple methods to quantify pollutant transport, rather than just one or two. This multi-pronged approach increased the ability of the project to meet its objectives and provided a way to evaluate the uncertainty or reliability of the various methods. Our technical approach included identifying and selecting methods, acquiring the data needed to apply them, applying the methods, and comparing and evaluating the results. In addition, we have analyzed the air flow characteristics in the Sacramento Valley, the San Joaquin Valley, and the SF Bay Area in order to provide a basic understanding of how, when, and where pollutant transport might occur; this understanding was a useful component of all other analysis methods.

First, we identified and selected methods to quantify the influence of transported pollutants on downwind ozone concentrations and identified the data required by these methods. The methods range from simple techniques which use only routine air quality and meteorological data to more complex techniques which require special field data. There was very little time between the award of the contract and the required field measurements, which had to take place in the summer of 1990 in order to coincide with the extensive field measurements being taken in and near the Sacramento Valley, including the Sacramento Area Ozone Study (SAOS) and the San Joaquin Valley Air Quality Study and Atmospheric Utilities Signatures, Predictions, and Experiments (SJVAQS/AUSPEX). Thus, there was not enough time before the field measurements to apply the selected methods to existing data sets and use the results to refine the field measurements.

Next, we planned the field measurements to acquire the data needed to apply the selected methods. Some of the needed data were routinely available, while other data had to be collected during an intensive field measurement program. The intensive field measurement program included perfluorocarbon tracer tests, aircraft and meteorological measurements aloft, and speciated measurements for many volatile organic compounds (VOC) species and several tracers of opportunity (chlorofluorocarbons-CFCs). A significant data validation effort was also performed in order to prepare the field data for use in the methods application tasks. A summary of the field measurement program is included in Section 2.

Based on a review of meteorological and air quality data, ARB staff (ARB, 1990a) were able to find evidence of significant pollutant transport from the SJVAB to the Broader Sac on only 1 out of 251 days when the state ozone standard was exceeded in the Broader Sac during 1986, 1987, and 1988. In addition, Hayes et al. (1984) did not find any cases of southerly flow during the summer; southerly flow is the only Sacramento Valley flow pattern type which might transport pollutants from the SJVAB to the Upper Sac. Based on these two analyses of historical data, it seems highly unlikely that any significant transport between the SJVAB and Upper Sac would occur during the summer of 1990. Thus, we focused the field study and subsequent data analyses on transport from the SF Bay Area and the Broader Sac to the Upper Sac.

In the final tasks of this project, we applied the selected methods, and compared and evaluated the results. When applying these methods, we chose to do so in steps. We applied several qualitative methods first, in order to focus the more detailed and time-consuming quantitative methods on the days and locations best suited to them, and to provide the meteorological and air quality characteristics for specific cases. Then we applied the selected quantitative methods for the cases of interest. In general, various methods were used:

- To evaluate if ozone or ozone precursor transport between the upwind and downwind areas had taken place;

- To evaluate when and how often ozone or ozone precursor transport between the upwind and downwind areas had taken place;

- To estimate the general path of ozone and ozone precursor transport between the upwind and downwind areas; and

- To estimate the relative contribution of upwind and downwind emissions to ozone exceedances in the downwind area.

The first three items deal with qualitative assessments of pollutant transport, while the fourth item deals with a quantitative assessment. Although the objective of this project was to develop methods to perform the quantitative assessments, we performed some qualitative assessments first in order to help focus the quantitative assessments on the days and locations best suited to those methods.

1.3 SUMMARY OF TRANSPORT METHODS USED DURING THIS PROJECT

Various data analysis methods can be applied to evaluate if, when, how, and how much ozone and ozone precursor transport has occurred. Some of these methods can also be used to estimate the relative contribution of transported pollutants to ozone violations. A summary of many potential methods is provided in a recent report on transport for the ARB (Roberts et al., 1992). Many of these have been used before to investigate various aspects of ozone and ozone precursor transport (for example, ARB, 1990a; Roberts et al., 1990; Roberts and Main, 1989; Douglas et al., 1991).

Our technical approach included applying multiple methods to a specific ozone episode in order to build a strong case for a transport assessment. This strength lies in the consensus conclusions drawn from applying multiple methods, not just in the conclusions drawn from applying only one or two of the methods. Sometimes during our analyses, the results from applying different methods did not agree; in those cases we illustrated the differences and based our conclusions on the most reliable ones.

A summary of the methods which we applied during this project is provided below; additional details are provided in Sections 4 through 9 on the individual methods. Some of the methods use only routine data, while others require special intensive measurements. Some of the methods require meteorological, air quality, and/or emissions inventory data. The methods which are capable of quantifying pollutant transport typically require routine and intensive data. We applied those data analysis methods which were best suited to the potential transport situation and which were supported by the available data.

Grid modeling could also be performed to quantify pollutant transport. For transport to the Upper Sac, model results from the SAOS or the modeling for SJVAQS/AUSPEX might be useful. However, neither modeling is finished, so the results cannot be compared with the data analysis results from this project.

1.3.1 Flow Characteristics

Surface Air Flow Pattern Types: These are the air flow patterns developed and used by the ARB meteorology section; they provide a snapshot of the air flow three times per day. Specific flow types are consistent with transport from one basin into another. For example, three of the SF Bay Area flow types would be consistent with transport into the Upper Sac: northwesterly, southerly, or bay outflow. The frequency and persistence of these flow types during and immediately preceding ozone episodes at downwind monitoring sites would support transport. This also might be considered as a "streamline" analysis, where the consistency of successive 4-hourly wind streamline maps are reviewed for transport potential (for example). An improved version using typical trajectories to classify flow types would better represent the integrated results of conditions that transport pollutants from a source to a receptor (a current ARB project will be applying this method to pollutant transport in and around the SF Bay Area Air Basin, see Stoeckenius et al., 1992).

The Presence or Absence of a Convergence Zone: A mid-valley convergence zone was often present in the morning in the area near Sutter Buttes; the convergence zone was often along a southwest/northeast line. Pollutant transport at the surface was blocked when the convergence zone was present; however, pollutant transport could still occur aloft.

1.3.2 Statistical Analyses

Diurnal Ozone Concentration Patterns: Analyses of the time of peak ozone concentration at various monitoring sites can yield useful information on transport patterns and source areas. In most major source areas of interest in California, transport winds are light in the morning, allowing ozone precursor concentrations to build up and ozone to form. By noon, transport winds generally increase and the ozone moves downwind out of the major source regions. This leads to peak ozone concentrations in the principal source areas around 1100 to 1300 PST with a decrease thereafter as the ozone-rich air is replaced by cleaner air from upwind. Peak ozone times after 1300 PST generally signify transport into the area from an upwind source region.

Correlations and Regressions: Pollutant transport to Upper Sac could be evaluated by performing correlations using daily maximum ozone concentrations in Upper Sac with the daily maximum ozone concentrations averaged over five highly correlated sites in the Broader Sacramento Area, using either a zero, 1-, and 2-day lag in the Broader Sac concentration. In addition, step-wise regressions could be performed, again using ozone parameters, but adding potentially important meteorological parameters.

1.3.3 Trajectory-based Methods

Air-Parcel Trajectories: Air-parcel trajectories estimate the path of an hypothetical air parcel over a selected time period. Back trajectories follow an air parcel to illustrate where the air might have come from; forward trajectories follow an air parcel on the way from a source region to illustrate where an air parcel might go. Back trajectories using surface winds were prepared for high ozone concentrations at Upper Sacramento Valley receptor sites; trajectories will show if pollutants might have come from the SF Bay Area, Broader Sac, or just Upper Sac. In addition, available upper-air wind measurements can be used to estimate aloft trajectories and the potential contribution of aloft pollutants to ozone exceedances in the Upper Sacramento Valley. Days with similar trajectories (i.e., trajectories that follow similar paths and originate in the same source region at roughly the same time of day) can be grouped together into ensembles or categories.

Relative Precursor Contribution Estimates: There are a number of methods to estimate the relative emissions contributions to downwind ozone exceedances, ranging from simple to more complex. As the method gets more complex, the strength of the transport conclusion increases. The method we have used includes estimating the relative emissions contributions by separately accumulating emissions from the various air basins along a typical trajectory path. We have included a net reaction rate to account for the losses of precursor via chemical conversion, deposition, and dry deposition. This method will provide an estimate of the relative contributions of upwind basins to receptor ozone concentrations.

1.3.4 Pollutant Flux Estimates

Simple Pollutant Flux Plots: One method uses routine pollutant and wind measurements at one monitoring site to estimate the relative flux of pollutants across an imaginary boundary. Simple pollutant flux plots show the product of surface pollutant concentration and surface wind speed in the direction perpendicular to a plane specific to the measurement site. Results from using this method can represent the two-dimensional (2-D) transport of pollutants across a boundary only during well-mixed conditions, but the availability of routine data provides pollutant-transport information at many times. The diurnal pattern of concentration and flux can be reviewed for many days using this method.

Pollutant Flux Estimates: Another method uses upper-air meteorological and air quality data to estimate the flux of pollutants across a 2-D plane at the boundary between Upper Sac and Broader Sac. The data needed for this method were collected by aircraft and balloon soundings; these data were only available during intensive sampling. The spatial pattern of pollutant concentration, winds, and flux was estimated across this 2-D plane. The flux of ozone and of NO_x can vary spatially across this plane.

Note that although these flux methods can estimate the pollutant transport at the boundary, they cannot quantify the contributions of the upwind areas separately.

1.3.5 VOC Species and Tracers-of-Opportunity Analysis Methods

Analysis of VOC species and tracers-of-opportunity (CFCs) data were performed to investigate source area compositions and relative contributions to receptor compositions. Three analysis methods were used: (1) the identification and use of unique VOC and tracers-of-opportunity signatures for each of the upwind air basins, the SF Bay Area and Broader Sac; (2) the age of the arriving air parcels; and (3) statistical analyses.

Visual comparisons of VOC and tracers-of-opportunity signatures, plus cluster and factor analyses, were used to identify groupings of samples which had similar characteristics.

An estimate of the age of arriving air parcels can be prepared using VOC species ratios. For example, ratios of toluene to benzene (T/B) and the sum of m- and p-xylenes to ethylbenzene can be used as an indication of the relative age of an air parcel in the atmosphere. These are ratios of similar compounds with the most reactive on top (i.e., toluene reacts faster than benzene). Thus, the lowest ratios would correspond to the most aged air parcel.

1.3.6 Tracer Analysis Methods

The approach included releasing different tracers to represent emissions from the SF Bay Area and the Broader Sac and to quantify the relative contribution of these areas by measuring tracer concentrations at Upper Sac receptor sites. In addition, the spatial and temporal pattern of tracer concentrations can be used to document the transport path and the transport speed.

1.4 SUMMARY OF OVERALL PROJECT CONCLUSIONS

Listed below is a summary of overall project conclusions, including a discussion of which methods worked and which methods show promise for future applications in the Upper Sacramento Valley. More details are provided in Section 10.

- Characterizing the air flow of the region provided a basic understanding of how, when, and where pollutant transport might occur; this understanding was essential as a first step in any transport study. In addition, statistical techniques can help identify which receptor sites are influenced by pollutant transport.

- Generating large numbers of air-parcel trajectories was a good method of identifying the consensus transport paths for each receptor. However, both surface and aloft wind measurement data are needed to generate air-parcel trajectories for all receptor sites and situations, since aloft pollutant transport can often occur.

- During this project, the combined surface trajectory/precursor contribution estimate method worked best when applied to pollutant transport to Chico, versus transport to Red Bluff or Redding. This was due to the possibility of regular aloft transport to Redding and Red Bluff, but we did not have sufficient aloft data to apply these methods. If appropriate aloft data were available, the method should work as well for transport to Red Bluff and Redding.

- Simple pollutant flux estimates were very useful in identifying the temporal characteristics and relative magnitude of pollutant fluxes at a boundary site between two air basins. This method is also useful in designing a measurement program to collect data for tracer and 2-D flux plane studies.

- Estimating pollutant fluxes using 2-D flux plane measurements was a direct and useful method to quantify pollutant transport. However, frequent pollutant and wind measurements aloft (more than three times per day) are required in order to capture the appropriate conditions which relate to peak ozone at a downwind receptor.

- Routine air quality and meteorological measurements taken at an isolated, elevated location, such as a radio tower or Sutter Buttes, for example, are representative of conditions aloft at an equivalent altitude. Data from such a site represent a cost-effective method for collecting pollutant flux data aloft.

- Since we did not collect data during typical flow conditions in the Sacramento Valley, we were not able to quantify the relative contributions of the SF Bay Area and Broader Sac to an Upper Sac ozone exceedance. We did identify unique VOC and tracers-of-opportunity signatures for the Broader Sac and clean air resulting from northwesterly flow in the SF Bay Area, but not for the more urban/industrial SF Bay Area; however, the method appears promising for future applications.

- The tracer releases provided evidence of both surface and aloft pollutant transport from the SF Bay Area and the Broader Sacramento Area to Upper Sac receptor sites, even though the wind flow patterns were not typical and much of the tracer was carried into the foothills of the Sierra and not up the Sacramento Valley.

- A simple ozone/tracer regression analysis using the Redding data provided estimates of the relative amounts of ozone contributed by various areas. Since these samples did not contain Howe Park tracer, the contributions of the Broader Sac and Upper Sac could not be separated. If the Redding samples had included significant Howe Park tracer concentrations, then the relative contributions for the Upper Sac, Broader Sac, and SF Bay Area could all have been estimated.

1.5 SUMMARY OF RECOMMENDATIONS FOR FUTURE METHODS APPLICATIONS IN THE UPPER SACRAMENTO VALLEY

The data analysis methods which could be applied in future applications for the Upper Sac include transport paths and precursor contribution estimates using surface and aloft trajectories, 2-D pollutant flux estimates, ozone/tracer regressions, and analyses of unique VOC and exotics signatures. In addition, air flow patterns should be characterized as a basis for any of the other methods. At least two of the methods should be applied at the same time, in order to strengthen the results. If routine, hourly measurement techniques are used, then the selected methods can be applied to a wide range of high-ozone cases over a complete range of air flow characteristics.

If additional pollutant transport quantification for the Upper Sac is desired on more days and/or under a broader range of flow characteristics than addressed in this project, then we make the following recommendations:

- If future applications for the Upper Sac are limited to the use of existing aerometric monitoring, then only one method which we studied is possible: precursor contribution estimates for NO_x and ROG using surface trajectories (see Section 6). This method is not applicable to all Upper Sac receptors, but only to those receptors which are influenced by same-day surface transport. This would include receptor sites south of a diagonal line between Maxwell and Chico. In addition, air flow patterns should be characterized for all days of interest as a basis for understanding and interpreting the analysis results.

- If new routine monitoring is installed to meet EPA's PAMS (Photochemical Assessment Monitoring Stations) requirements for the Sacramento Metropolitan Air Quality Management District (see EPA, 1992), then VOC signature analyses could be performed to quantify precursor transport. The PAMS requirements include hourly VOC-speciation measurements at upwind, Sacramento urban, and downwind locations. If a similar monitor was also installed at one or more Upper Sac receptors (for example, Redding, Chico, and/or Red Bluff), then the VOC-signature analysis described in Section 8 could be performed. This technique enables the potential identification of the source of the air parcel based on the VOC signature if these signatures are observed to differ among source regions. In addition, air flow patterns should be characterized for all days of interest as a basis for understanding and interpreting the analysis results.

- Based on analyses in this study, if additional measurements can be taken such that 2-D flux plane and VOC-signature analysis methods can be employed, the combination of these techniques provides the most reliable quantification of ozone and ozone precursors. These methods are reliable because they are based on calculations and comparisons using physical parameters such as wind speed, wind direction, ozone concentration, and VOC speciation rather than relying on purely statistically related parameters which may not be physically related such as the timing of ozone peaks. To apply these two methods, intensive field measurements would be needed on potential transport days, including the following:

- Upper-air meteorological and air quality data at the Upper Sac upwind boundary to quantify the ozone and NO_x flux into the Upper Sac;

- Upper-air meteorological and air quality data at the Broader Sac upwind boundary to quantify the ozone and NO_x flux from other upwind air basins; and

- Speciated VOC measurements to represent the upwind areas (Broader Sac and SF Bay Area) and at Upper Sac receptor sites; data from the EPA PAMS network (mentioned above) could possibly be used to provide some of this data.

Note that the measurement locations for any of the studies mentioned above will depend on the then-current definition of the Upper Sac and Broader Sac areas.

1.6 REPORT CONTENTS

The remaining sections of this report provide an overview of the field study (Section 2); background information on important issues (Section 3), and on air flow patterns in the Sacramento Valley (Section 4); details on each analysis method and results of applying that method (Sections 5 through 9); and conclusions and recommendations (Section 10). Additional details and data summaries are provided in the appendices.

2. FIELD STUDY OVERVIEW

2.1 INTRODUCTION AND BACKGROUND

As a part of this project, a field study was conducted in the Upper Sacramento Valley (Upper Sac). The field study was designed to collect the data required by the methods described in Section 1. This section summarizes the field study effort; details are available in various reports on the individual measurement components (Prins and Prouty, 1991c and 1991d; Hansen et al., 1991a and 1991b; Rasmussen, 1991; and Tracer Technologies, 1991).

The field study design was based on the then-current understanding of pollutant transport and took advantage of other data collection efforts during July and August 1990. These included the San Joaquin Valley Air Quality Study (SJVAQS); the Atmospheric Utility Signatures, Predictions, and Experiments (AUSPEX); and the Sacramento Area Ozone Study (SAOS).

To meet the overall project objectives and the data needs of the data analysis methods discussed in Section 1, the field study measurements were performed within a 10-week period spanning from July 9, 1990 to September 13, 1990. Intensive sampling was performed during three 48-hour periods spanning 3 days: July 11-13, August 10-12, and September 11-13. The study was originally designed to end in mid-August; however, the field study window was extended in order to perform sampling during a third intensive period.

The field study was designed to address transport from the San Francisco Bay Area (SF Bay Area) and from the Lower Sacramento Valley (Broader Sac) into the Upper Sac. The field study did not perform any intensive measurements to address transport from the San Joaquin Valley (SJV) to the Upper Sac.

The following types of data are required in order to apply the data analysis methods discussed in Section 1.3. The data are needed at important receptor sites in the Upper Sac, in the upwind air basins, and along the upwind boundary of the Upper Sac.

- Routine hourly air quality and meteorological data, including measurements for ozone, NO, NO_x, particle scattering, wind speed, and wind direction. In addition, speciated volatile organic compound (VOC) data are needed.

- Intensive air quality and meteorological data aloft, including measurements for ozone, NO, NO_x, particle scattering, wind speed, and wind direction. In addition, speciated volatile organic compound (VOC) data are needed.

- Injected tracer concentration data at surface and aloft sites.

- Concentration data for various tracers of opportunity, including VOC and chlorofluorocarbons-CFCs species.

2.2 FIELD STUDY COMPONENTS

The field study was designed to provide the data necessary to apply the selected methods and to fit within the budget requirements of the project. Not all measurements that might have been desired were possible within the project budget. Field sampling was performed on three 3-day periods on a forecast basis. We attempted to sample during a 2-day episode of pollutant transport to the Upper Sac, including at least 1 day with high ozone concentrations at Upper Sac monitoring sites.

Components of the proposed field study are discussed below. We included components which are critical to the selected methods and as many measurements as we could, given the budget constraints of the project.

2.2.1 Air Quality Monitoring Network

Data from the existing routine ARB air quality monitoring network, including ozone, NO, NO_x, and particle scattering (b_{scat}) measurements were used in our analyses. We also recommended that the ARB reinstall ozone monitoring equipment at Colusa and Arbuckle (monitoring for ozone was discontinued before 1989) and at Red Bluff for the summer 1990 season. This would have complemented the existing network, which is sparse in those areas, and would have provided additional continuous information on ozone in the region of interest. However, only an ozone monitor was added at Red Bluff. As part of the SAOS, additional ozone monitors were operated at Lincoln, Nicolas, Tyndall, Sloughhouse, Lambie, and Cool; these data were also available for our analyses.

Two additional ozone monitoring sites were operated during the study period. These sites were located along the upwind boundary at Maxwell and on top of Sutter Buttes. These were inexpensive installations using existing shelters and power. A preliminary review of the 1989 SAOS results from the ozone monitor that we installed at Sutter Buttes indicated that ozone concentrations at that site were often typical of aloft concentrations measured by aircraft, and were typically higher than surface concentrations at night when concentrations in the surface layer are often reduced by fresh NO emissions. Upper-air meteorological and tracer sampling were also performed at Maxwell, while tracer samples were also collected at Sutter Buttes.

2.2.2 Meteorological Monitoring Network

Data from the existing routine meteorological monitoring network, including the additional surface meteorological stations installed for the SAOS, and the two doppler acoustic sounders installed for the SJVAQS/AUSPEX, were available for our analyses.

Upper-air meteorology measurements of wind speed and direction, temperature, and relative humidity were performed along the upwind boundary of the Upper Sac at Maxwell and North Yuba. The data were collected to provide the aloft wind speed and direction for estimating pollutant fluxes, and for estimating aloft trajectories into the Upper Sac. Soundings were taken four times each intensive day (coinciding with aircraft spirals when possible). Upper-air data were also available from four additional sites in the

Sacramento area during the July 11-13 period when the SAOS data collection coincided with this study.

2.2.3 Air Quality Aircraft

An air quality aircraft was operated to measure ozone, NO, NO_x, temperature, and particle scattering (b_{scat}), and to collect grab samples for later analysis for speciated C1-C10 hydrocarbons and tracers of opportunity (primarily chlorofluorocarbons-CFCs). Carbonyl measurements were originally proposed, but were eliminated because data interpretation for these mixed primary and secondary species is difficult and because the carbonyls are not of primary importance. The aircraft provided aloft air quality data and the ozone and precursor data for estimating pollutant fluxes into the Upper Sac. The aircraft also collected aloft grab samples for later tracer analyses.

Five flights were performed during each 3-day intensive sampling period. One flight was performed along a boundary drawn across the Sacramento Valley near Sutter Buttes, and included six vertical spirals from near the surface to about 1500 m, plus two traverses at about 300 m msl and 600 m msl. This boundary flight was performed on the first afternoon of the 3-day period (see Figure 2-1 for typical flight path; sampling locations are described in Table 2-1). Two flights per day were performed on the next 2 days of each period, with seven vertical spirals during each flight. The morning flight documented conditions at the upwind boundary and various receptor locations in the Upper Sac before daylight-induced mixing had occurred (see Figure 2-2 for typical flight path). The afternoon flight documented conditions during the time of peak ozone concentrations and maximum ozone transport (see Figure 2-3 for typical flight path).

The aircraft also collected grab samples for VOC species which were later analyzed for speciated C1-C10 hydrocarbons, plus some CFCs. The VOC results are critical for understanding the ozone formation potential of pollutants entering the Valley; the CFCs are potential inherent tracers for the upwind air basins. About 75 grab samples were taken in the aircraft.

2.2.4 Perfluorocarbon Tracer Tests

A perfluorocarbon tracer test was performed during each intensive. Each test included the release of four different tracers, two at each of two source-area release sites, and the analysis of tracer samples collected aloft and at 12 surface sites. The aloft samples were typically collected from about 150-180 m (500-600 ft) and 600-900 m (2000-3000 ft) during aircraft spirals; the surface samples were 2-hour averages. The release sites were located at Lambie Road, just east of Travis Air Force Base (to represent pollutants from the SF Bay Area) and at Howe Park, just east-northeast of downtown Sacramento (to represent the Broader Sac). The times of the releases (first afternoon of each intensive period and the next morning) were designed to coincide with times of peak transport, and with the afternoon and morning rush hours. A map showing the tracer release and surface and aircraft sampling sites is shown in Figure 2-4. About 455 analyses for the tracers were performed. The 455 analyses were split between samples taken from the

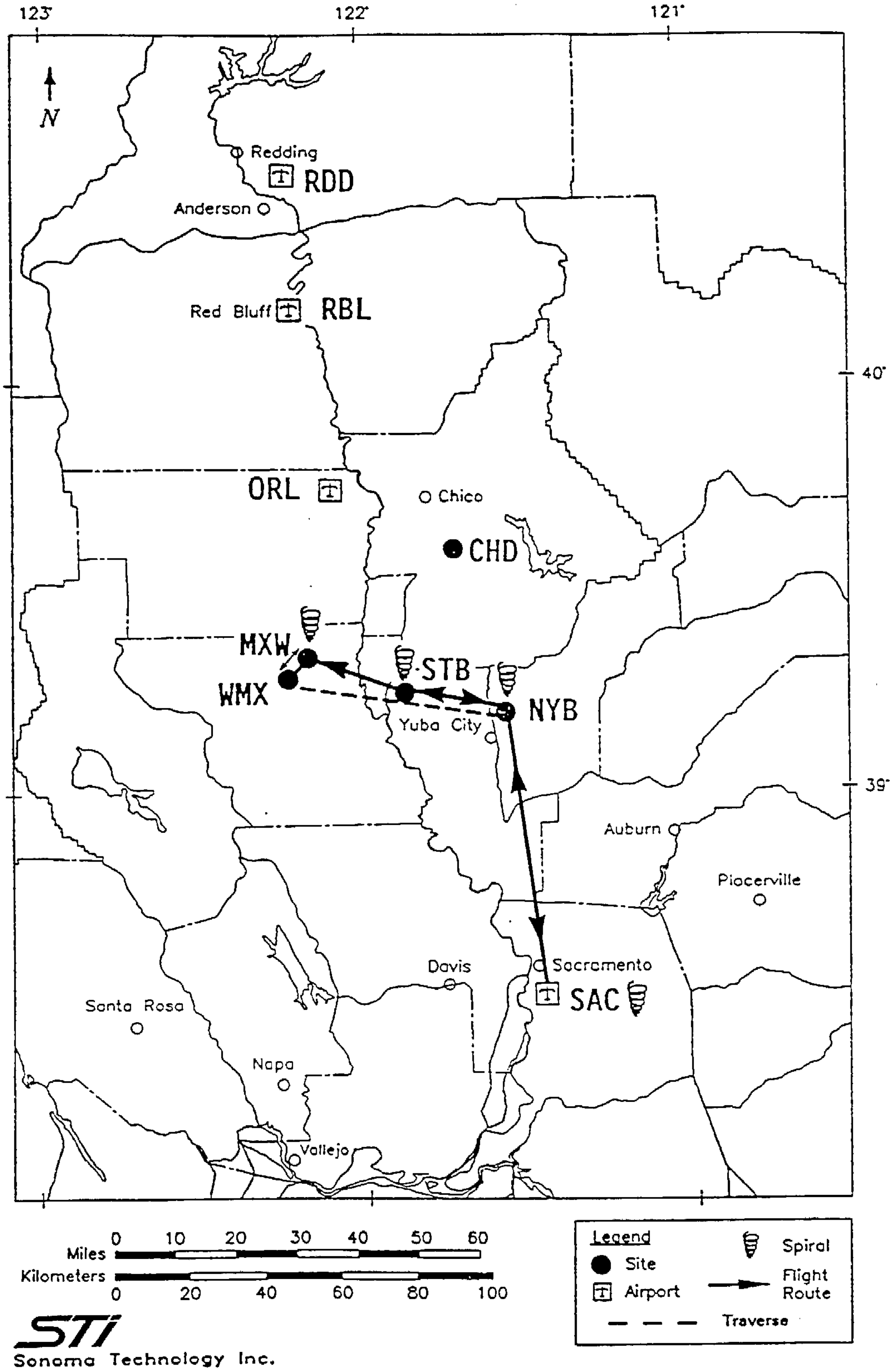


Figure 2-1. Example STI aircraft flight pattern on first afternoon of intensive sampling: Flight 605 on August 10, 1990, 1348-1733 PDT.

Table 2-1. Summary of STI aircraft sampling locations during the 1990 Upper Sacramento Transport Study.

Sampling Location Identification	3 Letter Map Abbreviation	Coordinates	
		Latitude	Longitude
North Yuba	NYB	N 39 ° 13.00'	W 121° 34.00'
WNW of Sutter Buttes	STB	N 39 ° 15.00'	W 121° 54.00'
Maxwell	MXW	N 39 ° 19.42'	W 122° 12.43'
5 mi. W. of Maxwell	WMX	N 39 ° 17.12'	W 122° 17.36'
Chico	CHD	N 39 ° 35.67'	W 121° 44.36'
Orland/Haigh	ORL	N 39 ° 43.30'	W 122° 08.70'
Red Bluff Airport	RBL	N 40 ° 09.10'	W 122° 15.10'
Redding Municipal Airport	RDD	N 40 ° 30.60'	W 122° 17.50'
Sacramento Executive Airport	SAC	N 38 ° 30.80'	W 121° 29.60'
Sacramento Metropolitan Airport	SMF	N 38 ° 42.00'	W 121° 36.00'
Santa Rosa Airport	STS	N 38 ° 30.60'	W 122° 48.70'

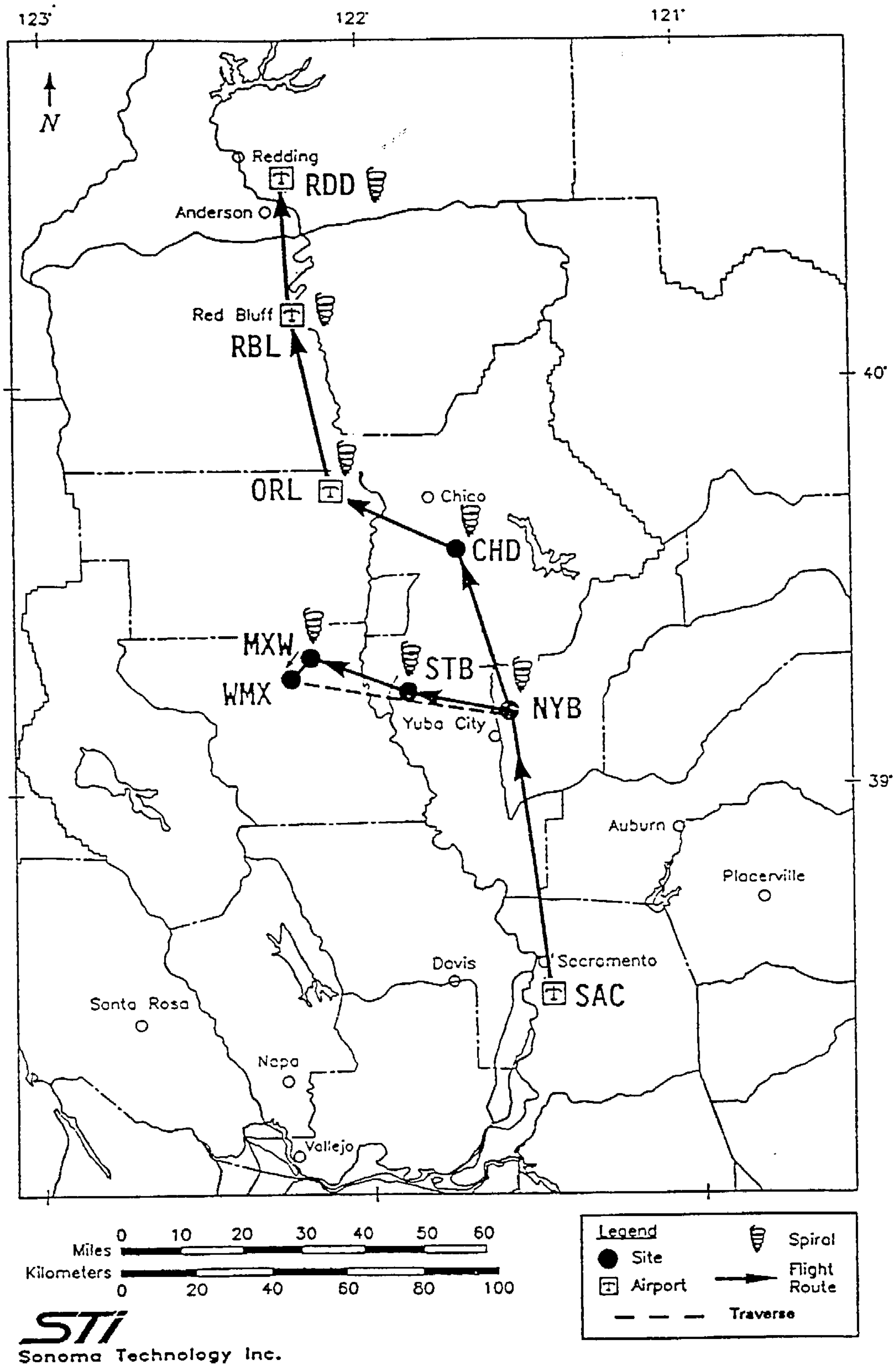


Figure 2-2. Example STI aircraft morning flight during intensive sampling: Flight 606 on August 11, 1990, 0535-0834 PDT.

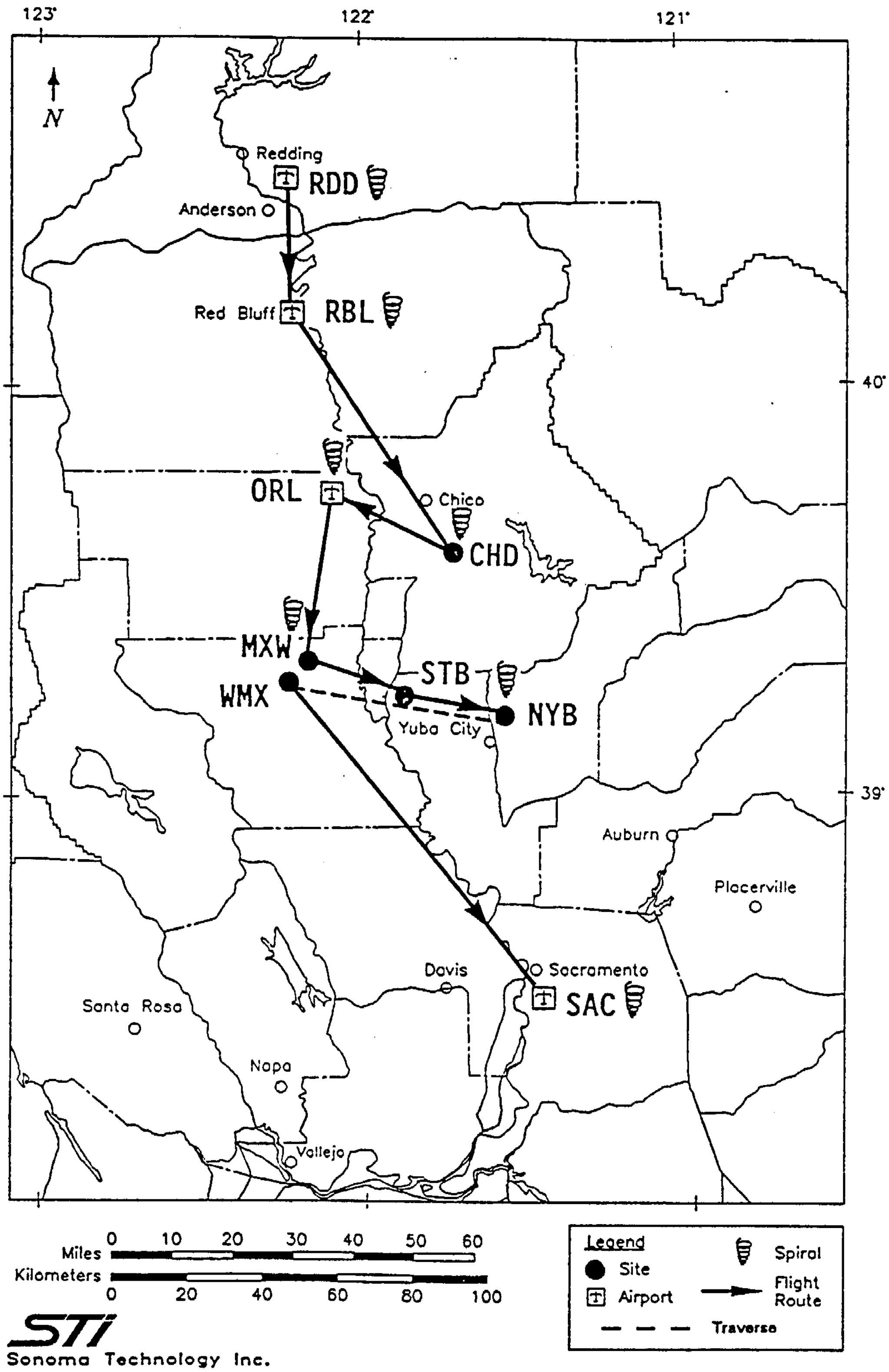


Figure 2-3. Example STI aircraft afternoon flight during intensive sampling: Flight 607 on August 11, 1990, 1328-1627 PDT.

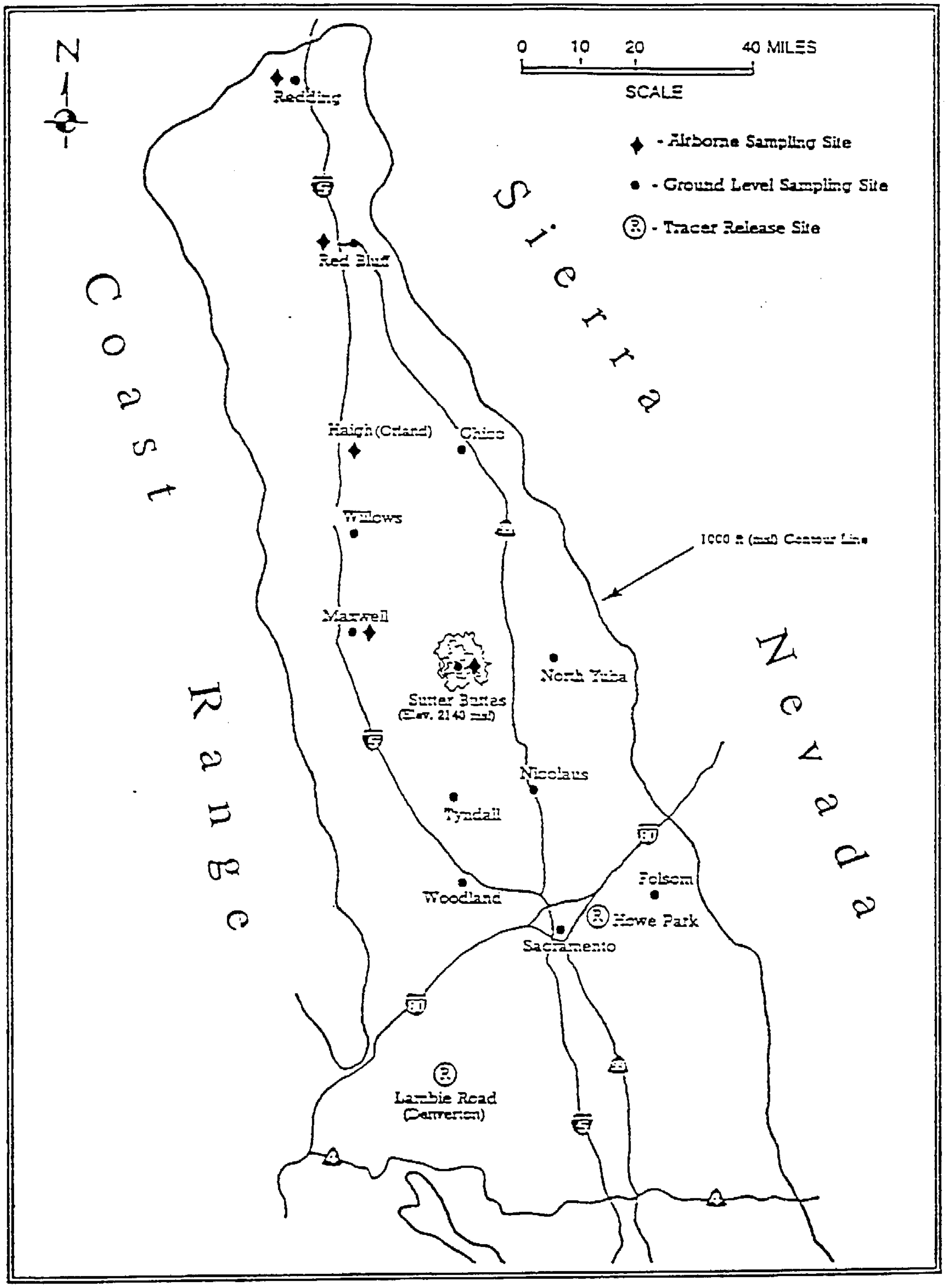


Figure 2-4. Map of tracer release, aircraft sampling, and ground sampling sites. From Tracer Technologies, 1991.

STI aircraft and at surface sampling locations. In particular:

- Since ozone concentrations at Upper Sac sites were low, no tracer samples were analyzed for the September intensive period.

- 150 grab samples were collected from the STI aircraft for later analysis for tracers (about 50 per test); all of the July and August samples were analyzed.

- For each tracer test, 24 to 27 2-hour samples were collected at each of the 12 surface sites during the two days following the tracer release (about 300 samples for each test, or 900 total samples). Since we expected that many samples would not contain any tracers, and since we needed to conserve funds, the samples were analyzed in two parts. First, we analyzed 6 of the 12 samples taken over a 24-hour period at each site when pollutant impact was predicted to be highest (using air quality and other data), plus a few additional samples. Then we selected which additional samples would best fill in, for a total of 355 surface sample analyses.

2.2.5 Field Management

Many individuals representing a large number of organizations participated in this study. The field management component provided overall planning and direction during the intensive monitoring period, and coordination of the field operations and subsequent data base preparation and documentation efforts.

In addition, the tracer tests had to be coordinated with the tracer tests being performed for the ARB (transport into the Sierra) and for the SJVAQS (transport into the SJV). Tracer Technologies performed the tracer tests for all three projects using the same perfluorocarbon tracers. Since tracer released for any of the three projects could have been transported to sampling sites set-up for the other projects, sufficient time had to be allowed between tests for the tracer to clean out. Since the SJVAQS tracer tests had the highest priority, they got first choice to release tracer. This meant that we could not always perform our tests on the days we wanted; this occurred during August when we would have selected to start our test on either August 5 or 6, but could not.

3. TECHNICAL ISSUES

This section summarizes a number of important technical issues which must be considered when determining an approach to quantifying pollutant transport and evaluating pollutant quantification results. Transport of air pollutants between air basins occurs when there are winds of sufficient speed, duration, and direction. Transport may occur either in the surface layer or aloft. Both ozone and ozone precursors (e.g., hydrocarbons and nitrogen oxides) may be transported. In general, the impact of pollutant transport on the ozone air quality in a downwind air basin is influenced by the following:

- The precursor emission rates in the upwind air basin;
- The losses of pollutants by reaction and deposition along the transport path;
- The formation of ozone along the transport path;
- The meteorological conditions which transport and mix the pollutants; and
- The local precursor emissions in the downwind air basin.

The geography of the upwind and downwind regions also influences the potential transport path and the amount of transport between air basins. In addition, the availability of surface and aloft meteorological and air quality data is an important consideration in determining which analysis methods could be applied to quantify pollutant transport between air basins.

3.1 OZONE FORMATION

Ozone is not emitted directly into the atmosphere, but is formed via a series of reactions involving sunlight, organic compounds, and nitrogen oxides. Three reactions illustrate the ozone cycle (Seinfeld, 1986). The formation of ozone begins with the photodissociation of nitrogen dioxide (NO_2) in the presence of sunlight:

$$NO_2 + \text{sunlight} \longrightarrow NO + O \qquad (1)$$

The atomic oxygen (O) quickly combines with molecular oxygen (O_2) to form ozone (O_3):

$$O + O_2 \longrightarrow O_3 \qquad (2)$$

Once formed, ozone reacts with NO to regenerate NO_2:

$$NO + O_3 \longrightarrow NO_2 + O_2 \qquad (3)$$

Most of the nitrogen oxides emitted into the atmosphere are emitted as NO; if ozone exists near where the NO is emitted, then the NO will reduce ozone concentrations by scavenging. However, volatile organic compounds (VOC, including hydrocarbons and carbonyls) contribute to the conversion of NO to NO_2 without consuming ozone; this increases the ozone concentration.

In order to quantify the transport contribution to ozone concentrations at a downwind receptor, the transport of both ozone and ozone precursors must be considered. As described above, the major precursors are NO_x (including NO and NO_2) and VOC. Note that the concentration of NO_x required to keep the ozone-formation chemistry sustained in an atmosphere with sufficient VOC emissions is quite low: a concentration of about 3 to 5 ppb NO_x will continue to form ozone at a very efficient rate. Thus, injection of small amounts of NO_x emissions along a transport path will continue to form ozone and keep the ozone concentration well above background concentrations.

3.2 PRECURSOR EMISSIONS

Ozone is not emitted directly into the atmosphere, but is formed via photochemical reactions of other species. Therefore, it is important to understand the emission rates of the ozone precursor species in the upwind and downwind air basins. There are a number of methods available to estimate the relative emissions contributions of upwind and downwind areas to downwind ozone exceedances. In this study we selected a method which accumulates the emissions from the various source regions along a typical trajectory path and allows for average losses via reaction and deposition along the way. Using this method, the presence of emissions in an arriving air parcel indicates that emissions could have been transported to the receptor. However, this estimated relative contribution is not an estimate of the amount of ozone formed from upwind precursors during transport along the trajectory; this can only be addressed with modeling. We have assumed that the relative amount of precursor contribution to precursor concentrations in an arriving air parcel is related to the potential to form ozone and thus is related to the amount of ozone formed recently from upwind precursors.

The most important precursor emissions are oxides of nitrogen and VOC, including hydrocarbons and carbonyls. These compounds are generally associated with anthropogenic activities such as fuel combustion and architectural coatings. In the Sacramento Valley, however, emissions of biogenic hydrocarbons from natural vegetation and commercial agricultural crops are additional sources of hydrocarbons along a transport path; these emissions must be included in any emissions-related analyses.

Since precursors are lost via reaction and deposition, the time of transport will have a significant influence on the amount of precursor still existing at the receptor site.

3.3 GEOGRAPHICAL SETTING AND RESULTING METEOROLOGICAL ISSUES

The geography of the upwind and downwind regions influences the potential transport path and the amount of transport between air basins. One of the initial steps in quantifying pollutant transport between air basins is to understand the geographical features which influence the air flow patterns between air basins. Prominent geographic features such as mountains, valleys, narrow canyons, and gaps in ridgelines often direct wind flow near the surface and aloft for several thousand feet. In addition, the geography can influence ambient temperatures near the surface and aloft; temperature differences can impact air movement both horizontally and vertically. For example, strong horizontal temperature gradients can induce air currents, while temperature changes in the vertical such as an inversion tend to reduce both vertical and horizontal air movement.

A description of the geographic setting for many of California's air basins can be found in ARB (1989 and 1990a). For example, the following excerpt is from the geographic description of the San Francisco Bay Area:

> "... the urbanized portions of the San Francisco Bay Area Air Basin are separated from the Central Valley by the interior branch of the Coastal Ranges. The air flow patterns are largely determined by the topography. As the prevailing westerlies approach the California coastline, they must either blow over the mountains or be funneled through gaps such as the Golden Gate, the Nicasio Gap (west of San Rafael), and the Estero Gap (west of Petaluma). On the eastern side of the Bay, the Carquinez Strait leading into the Sacramento River Delta is the major exit for westerly flow moving out of the region, but other exits exist."

In this project we applied methods for quantifying transport from the San Francisco Bay Area (SF Bay Area) and the Broader Sacramento Area (Broader Sac) to the Upper Sacramento Valley (Upper Sac). The specific wind flow patterns and geographical setting for this area are described in Section 4: Flow Characteristics. In summary, the westerlies which flow through the SF Bay Area reach Broader Sac via gaps in the interior coastal ranges near the Carquinez Strait and move northward up the Sacramento Valley, occasionally reaching Upper Sac. The precise eastward and northward penetration of the marine influx from the SF Bay Area is determined by pressure gradients created by temperature differences between the warmer interior and the cooler coastal areas, as well as synoptic-scale weather events.

3.4 OTHER ISSUES

Additional meteorological issues which must be considered include:

- The presence of a convergence zone or eddy might significantly influence the transport path, time, or even if transport occurs. For example, a convergence zone occurs regularly in the Sacramento Valley on summer mornings; this convergence zone restricts southerly transport at the surface.
- Three transport time-scales should be considered: same-day transport, overnight transport, and transported pollutants which remain overnight in the receptor area. How long it takes to transport pollutants to a

receptor site influences the amount of precursors lost via reaction, the amount of ozone formed, and the transport path taken by the precursors.

- Transport can take place either at the surface or aloft. Pollutants transported aloft can travel much longer distances in a short amount of time (because of the higher wind speeds aloft) before mixing down to the surface as a result of surface heating. In addition, pollutants transported aloft may travel in a different direction than the surface winds may indicate.

Additional issues which must be considered include:

- The contribution of each of the upwind air basins must be quantified separately, not just as a sum of all upwind air basin contributions. This requires the methods be capable of separating the contributions of two or more upwind air basins. If the methods use either inherent or injected tracers, or some other type of source profile; then the appropriate data must be collected or available for each upwind air basin, and the unique signature for each basin must be different.

- Any quantification method must be capable of separating the relatively different contributions for the following two scenarios:

  (1) Ozone is formed in the upwind air basin and then is transported to the downwind air basin; and

  (2) Precursor emissions from the upwind air basin are transported and react to form ozone along the transport path.

Depending on the scenario, the data analysis methods must account for the following issues: timing of the ozone peak, tagging of the upwind pollutants, transport path, and pollutant transported (ozone, NO_x, and/or VOC).

3.5 AVAILABILITY OF SURFACE AND ALOFT METEOROLOGICAL AND AIR QUALITY DATA

In selecting appropriate methods for quantifying transport, it is important to recognize that all areas in California have very limited routine air quality and meteorology data aloft, and very limited data on VOC speciation and thus reactivity. The transport of pollutants aloft and VOC speciation are critical to quantifying ozone formation and transport. In some areas of the state, special field studies have been conducted to obtain higher-density surface measurements and additional aloft data. As noted in Section 2, a special field study was conducted in the Sacramento Valley as part of this project. The data collected in that field study were used extensively in our analyses.

3.6 RELIABILITY OF FINDINGS

The uncertainties of the results of applying various transport quantification methods need to be estimated and evaluated. This requires that more than one method be applied, that the methods use different data and data analysis techniques, and that the methods be applied to as many difference transport cases as possible. By applying multiple methods using the same and different data and data analysis techniques, a consensus can be developed on the various characteristics of pollutant transport. If a variety of methods yield similar results, then the consensus conclusions can be considered more reliable.

4. FLOW CHARACTERISTICS

The purpose of this section is to describe the air flow patterns and potential ozone and precursor transport during typical summer days and during the July 11-13, 1990 and August 10-12, 1990 ozone episodes. For this discussion, we have compiled and reviewed air flow patterns and ozone concentrations in the San Francisco Bay Area (SF Bay Area), the Broader Sacramento Area (Broader Sac), and the Upper Sacramento Valley (Upper Sac). The air flow and ozone concentration patterns provide a basic understanding of how, when, and where pollutant transport might occur; this understanding was a useful component of all other analysis methods.

4.1 TYPICAL AIR FLOW PATTERNS IN THE SACRAMENTO VALLEY

On a typical summer day, marine air penetrates the Sacramento Valley in the early afternoon and continues into the night. During the night, drainage flows along the slopes of the mountains which bound the valley on the north, east, and west sides tend to fold the sea breeze back around on itself (ARB, 1989). By morning, when the marine influx is weakest, the winds in the southern end of the valley swirl in an eddy (called the Schultz eddy). The strength of the marine influx varies from day-to-day, depending on the larger-scale pressure gradients. In the early evening, a low-level jet can be formed which is capable of long-range transport up the Valley. As reported in California Surface Wind Climatology (Hayes et al., 1984), the sea breeze wind pattern occurs about 75 percent of the afternoons during the summer ozone season in the Sacramento Valley (see Type I in Figure 4-1). The second most common afternoon wind pattern is northerly flow (see Type V in Figure 4-1), which occurs only about 10 percent of the time in the summer.

The ARB routinely plots surface wind direction and speed three times daily (e.g., 0400, 1000, and 1600 PST). ARB also performs a streamline analysis of each wind plot and classifies the wind patterns in each major air basin for each wind plot. We reviewed both the wind plots and wind types assigned by the ARB for northern California. Figure 4-1 shows air flow pattern types for the Sacramento Valley. Note that these flow types indicate surface flows only, and thus ignore possibly different flow types aloft and potential pollutant transport aloft. In this figure, two key indicators can be used qualitatively to understand pollutant transport: the arrows indicate the general direction of pollutant transport, while the presence of a convergence or divergence zone will indicate a major barrier to pollutant transport.

As shown in Figure 4-1, pollutants from the SF Bay Area and the Broader Sac can reach Upper Sac monitoring sites under flow type I; can reach Chico, but not Red Bluff and Redding under flow type II; and cannot reach either Chico, Red Bluff, or Redding under flow type III. Although flow type I dominates during summer afternoons, as mentioned above, and is the major type at other times of the day, flow types II and III occur regularly (15-25 percent of the time) overnight and in the early morning. Therefore, surface transport of pollutants to Upper Sac monitoring sites can often be restricted.

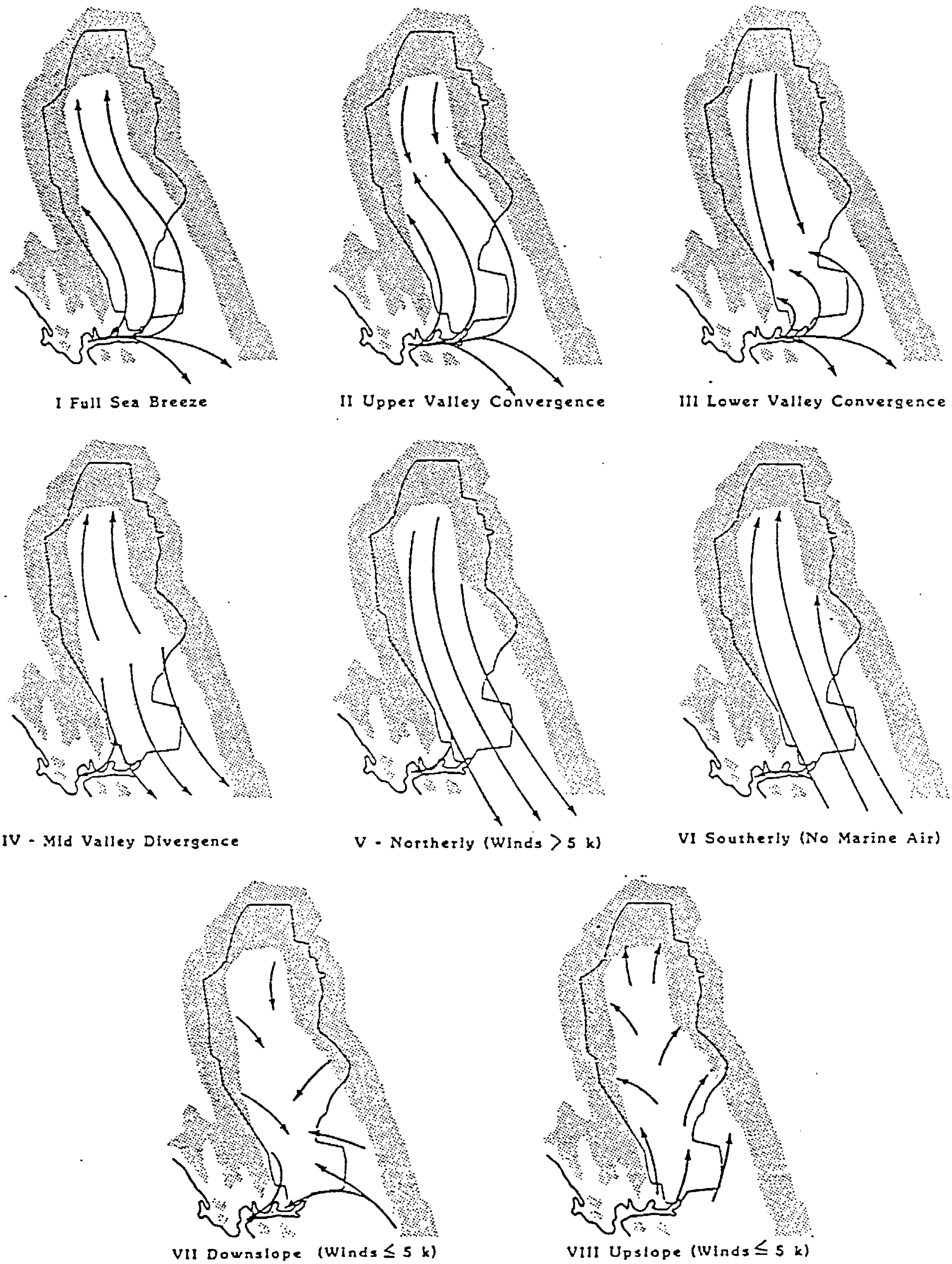


Figure 4-1. Sacramento Valley air flow pattern types. (From Hayes, et al., 1984.)

Figure 4-2 shows the air flow pattern types for the SF Bay Area. Pollutants from the SF Bay Area can be transported into the Sacramento Valley under types Ia, Ib, II, or VI. Types Ia and Ib are dominant (77 to 97 percent) at all times during the summer, with the only other significant pattern being type VI at 13 percent in the morning. This implies that most of the time, potential SF Bay Area transport contributions to the Sacramento Valley occur under northwesterly flow. Under northwesterly flow, pollutant emissions from northern portions of the SF Bay Area are the most likely to be transported into the Sacramento Valley. These emissions are relatively clean when compared to the pollutant emissions from most of the heavily urban and heavily industrial portions of the SF Bay Area, which are unlikely to be transported into the Sacramento Valley under northwesterly flow.

For a better understanding of the (relatively clean air) flow across the northern portions of the SF Bay Area into the Sacramento Valley, it was necessary to reclassify some of the wind types assigned by the ARB to the SF Bay Area. In particular, wind patterns with southerly flow along the coast of San Francisco, northerly flow down the bay toward San Jose, and westerly flow through Vallejo were often classified as "northwesterlies" by the ARB. For this study we have reclassified this condition as "southerly" in order to identify that on these days, emissions from areas with higher emission densities may have impacted the Sacramento Valley. In addition, emissions from the urbanized portions of the SF Bay Area may also impact the Sacramento Valley on days with winds classified as "bay outflow." On days classified as "northwesterlies," however, areas with low emission densities (such as Petaluma and other "North-Bay" communities of the SF Bay Area) may have impacted the Sacramento Valley.

Table 4-1 shows the frequency of occurrence during the summer for each wind type on a climatological basis (from Hayes et al., 1984), and for the summer of 1990, before and after our reclassification. As a result of our reclassification of wind types in the SF Bay Area during the summer of 1990, we changed a substantial number of northwesterly flow types to southerly/ SF Bay Area outflow. Thus, the potential for ozone and precursors from the

Table 4-1. Percentage of occurrence of SF Bay Area air flow types during the summer.

Period	Source	NW	Southerly	SF Bay Area Outflow	Calm	All Others
1977-1981	Hayes et al., 1984	87	3	4	3	3
Summer of 1990	ARB, 1990b	82	11	4	3	0
Summer of 1990	This work	62	30	5	3	0

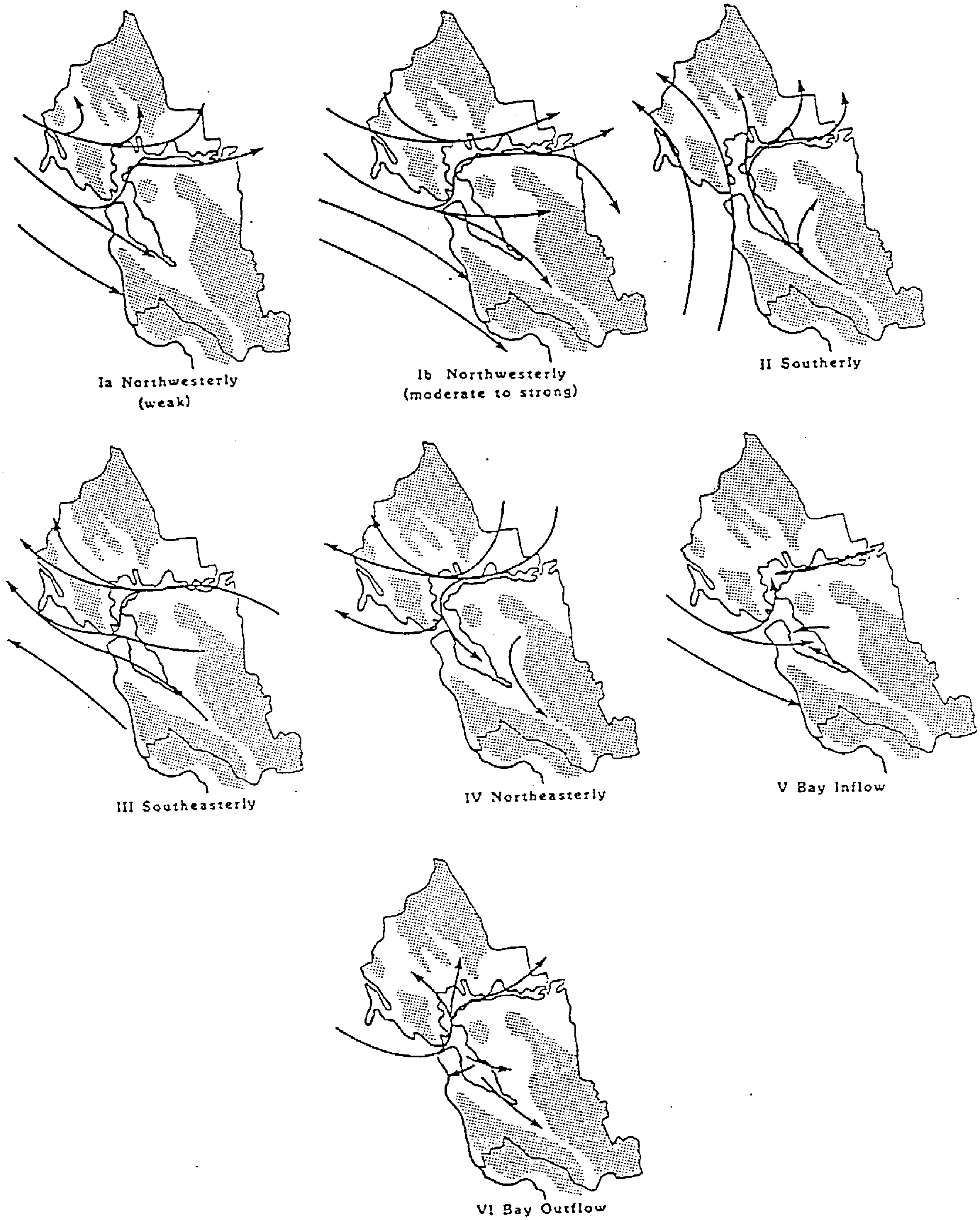


Figure 4-2. Bay Area air flow pattern types. (From Hayes, et al., 1984.)

urban portions of the SF Bay Area during the summer of 1990 was substantially higher than expected from the climatological norms. Table 4-2 shows the days with ozone concentrations of 9 pphm or greater from July 6 through August 14, 1990, for Upper Sac, Broader Sac, and SF Bay Area. Examination of the SF Bay Area wind flow patterns on 1990 ozone exceedance days in the Broader and the Upper Sac shows that 50 percent of ozone exceedances occur during the SF Bay Area southerly flow and 50 percent during the SF Bay Area northwesterly flow.

In addition, we reviewed the ARB streamline analyses for June 20 through August 18, 1990 to identify periods of potential transport from the San Joaquin Valley Air Basin (SJVAB) into the Sacramento Valley. These analyses were available three times per day; 0400, 1000, and 1600 PST. On only a few mornings was there any potential for transport into the Sacramento Valley from the SJVAB. But even on those days, the flow at 1000 PST had changed such that any pollutants from the SJVAB were carried into the Sierra foothills south of Placerville. Considering the potential dispersion and deposition during further transport and the high density of emissions in the Broader Sac, it is unlikely that any significant amount of SJVAB pollutants could have reached the Upper Sac.

4.2 DESCRIPTIONS OF FLOW PATTERNS AND MAXIMUM OZONE CONCENTRATIONS DURING INTENSIVE MEASUREMENT PERIODS

Each ozone event can be summarized by the direction of air flow at the surface and aloft and the measured ozone concentrations. However, particular attention should be given to several key indicators of wind patterns. The spatial and temporal patterns of the key indicators may be used as a guide in determining the extent of potential ozone or ozone-precursor transport from the SF Bay Area to the Broader Sac, from the Broader Sac to the Upper Sac, or from the Upper Sac to the Broader Sac. Intensive field monitoring was carried out during the periods discussed below. The field monitoring included a tracer study and aircraft and upper-air meteorological measurements. The air flow charts for each of the episode days discussed below are provided in Appendix A. Ozone concentrations referred to below are daily maximum concentrations (see Table 4-2 for a summary of maximum ozone concentrations for July 6 - August 14, 1990).

4.2.1 July 10-13, 1990 Episode

On July 10, 1990, the SF Bay Area maximum ozone concentration reached 13 pphm, the Broader Sac reached 10 pphm, and Red Bluff reached 11 pphm. Morning winds in the SF Bay Area were calm with some light southerlies, as were winds in the Broader Sac. Morning winds at Sutter Buttes (StB) and the Upper Sac were northerly with a convergence zone south of StB. Afternoon winds in the SF Bay Area were "Bay Outflow." Winds in the Broader Sac were from the north. Winds in the Upper Sac and near the StB were from the south (mostly upslope flow) creating a line of divergence.

On July 11, the day of the afternoon tracer release, the Broader Sac had a peak ozone concentration of 15 pphm, while no other portions of the region recorded high levels. On the morning of July 11, winds were from the northwest in the SF Bay Area, from the south in the Broader Sac, and from the

Table 4-2. Peak ozone concentrations (9 pphm or above) measured at Redding, Red Bluff, Chico, Sutter Buttes, Lower Sacramento Valley, and San Francisco Bay Area during July and August of 1990.

	Maximum Ozone (pphm) (a)					
Date	Redding	Red Bluff	Chico	Sutter Buttes	Sacramento (b)	SF Bay Area (c)
7/06						
7/07					10	
7/08		10				
7/09	9	10		9	10	
7/10	10	11		9	10	13
7/11				9	15	
7/12		12		9	15	12
7/13	9			9	11	
7/14		10		11	11	
7/15	11			11		
7/16						
7/17	9	11				
7/18	9			9	9	
7/19				11	10	
7/20					9	
7/21					10	
7/22	9					
7/23						
7/24						
7/25						
7/26				9	10	
7/27	9			9	10	
7/28	10	10		9	10	
7/29	11					
7/30	11			9	9	
7/31				10	13	
8/01				10	11	
8/02				9	9	
8/03	10		9	13	9	
8/04	11	11		11	15	
8/05	10	10		9	14	12
8/06	9	10	9	10	12	9
8/07	13	11	9	11	10	
8/08	9	10	12	10	15	13
8/09		10	13	9	11	12
8/10	10	10			9	9
8/11	9	10			9	
8/12	10	9			9	
8/13	11	11			11	
8/14	9					

(a) Peak ozone concentrations less than 9 pphm not listed.

(b) Highest ozone concentration in the Lower Sacramento Valley.

(c) Highest ozone concentration in the SF Bay Area Air Basin.

north in the Upper Sac, with a diagonal convergence zone near StB. Flow was northerly at StB. By 1000 PST, flows in the Broader Sac and the Upper Sac took on an upslope pattern with a north-south line of divergence running the length of the Sacramento Valley. By afternoon, weak southerly flow, with an eddy present in the Broader Sac, had penetrated up the Valley to include the Upper Sac, including southerly winds at StB.

On July 12, high concentrations of ozone were recorded in a widespread area (12 pphm in the SF Bay Area, 15 pphm in the Broader Sac, and 12 pphm at Red Bluff). Morning winds on July 12 were northwesterly in the SF Bay Area, light southerly in the Broader Sac, and light northerly in the Upper Sac, with a diagonal convergence zone near StB, which had northerly flow. At 1000 PST, flow in the Broader Sac was light northerly, although highly disorganized, and light northerly in the Upper Sac, with northerly flow at StB. Afternoon flow in the Broader Sac and the Upper Sac was mostly upslope with a southwesterly component in the Broader Sac.

On July 13, lower ozone concentrations were observed (11 pphm in the Broader Sac). The morning of July 13 was characterized by northwesterlies in the SF Bay Area, winds from the south in the Broader Sac, with a diagonal convergence zone south of StB. StB and the Upper Sac had northerly winds. At 1000 PST an eddy was present in the Broader Sac, and the convergence zone had been displaced to about Chico, although northerly winds remained at StB. By afternoon, southerly flow had covered the entire Sacramento Valley, including StB.

<u>Summary and Conclusions for July 10-13, 1990</u>

The July 10-13, 1990 ozone episode can be characterized in general as occurring during a period in which the typical diurnal sea breeze penetration into the Sacramento Valley was severely diminished. In fact, on July 10, winds were actually from the north in the Broader Sac and the SF Bay Area flow pattern prevented a strong sea breeze from reaching the Broader Sac. On July 11 and 12, the Broader Sac also experienced uncharacteristically weak southerly flow or completely northerly flow. On July 13 the typical strong afternoon sea breeze pattern returned and ended the ozone episode.

The implications of these flow patterns on ozone and precursor transport can be summarized as follows:

- Weak transport of SF Bay Area ozone and precursor emissions into the Broader Sac was likely on July 10.

- Transport of relatively low concentrations of SF Bay Area ozone and precursor emissions into the Broader Sac was possible on July 11 and 12.

- Ozone and precursor concentrations in the Broader Sac were dominated by north-south sloshing between the Broader Sac and the Upper Sac and possibly the northern San Joaquin Valley on July 11 and 12.

- Relatively clean air from the northern SF Bay Area was transported into the Broader Sac on July 13.

4.2.2 August 10-12, 1990 Episode

On August 10, 1990, a maximum ozone of 10 pphm was measured in the Upper Sac; other areas had lower ozone concentration. Winds in the SF Bay Area were northwesterly all day. Morning winds in the Broader Sac were southerly with a diagonal convergence zone north of Chico; StB winds were northwesterly. At 1000 PST, the southerly flow had penetrated much of the Upper Sac and StB winds were northeasterly. By afternoon, southerly winds had fully penetrated the entire valley floor, including StB.

On August 11, 1990, 10 pphm ozone was measured at Red Bluff. Winds in the SF Bay Area were northwesterly all day. Morning winds in the Broader Sac were southerly with an eddy present and a diagonal convergence zone north of Chico; StB winds were southerly. At 1000 PST, winds in the Broader Sac were southerly with a diagonal convergence zone south of StB. By afternoon, southerly flow had penetrated most of the Upper Sac, including StB.

On August 12, 1990, 10 pphm ozone was measured at Redding. Winds in the SF Bay Area were northwesterly all day. Morning winds in the Broader Sac were southerly, StB winds were southerly, and winds in the Upper Sac were light and variable. At 1000 PST, winds in the Broader Sac were southerly, influenced by upslope flows and an eddy; StB winds were southeasterly. A convergence zone south of Red Bluff separated the northerly flows in the Upper Sac from the southerlies at the surface which had penetrated north of StB. By afternoon, southerly flow penetrated all of the Upper Sac, including StB.

<u>Summary and Conclusions August 10-12, 1990</u>

The August 10-12, 1990 period can be characterized in general as occurring during a period in which the typical diurnal sea breeze penetration into the Sacramento Valley was present with relatively clean "north-bay" air entering from the SF Bay Area under northwesterly flows. In fact, the sea breeze was so strong that the Broader Sac remained "clean" throughout the period, never exceeding the state ozone standard (9 pphm). The implications of these flow patterns on ozone and precursor transport can be summarized as follows:

- Relatively clean air from the northern SF Bay Area was transported into the Broader Sac and the Upper Sac on August 10-12.
- Flow of ozone and precursors from the Broader Sac to the Upper Sac was likely on August 10-12.

4.3 SUMMARY OF CHARACTERISTICS DURING 1990 INTENSIVE SAMPLING

In this section we described the typical flow characteristics of the SF Bay Area, the Broader Sac, and the Upper Sac. We showed that the ozone episodes during the summer of 1990 during which intensive monitoring was conducted were not characterized by typical wind flow patterns. During the summer of 1990, there was significant potential for SF Bay Area impact at the Upper Sac sites, due to the greater-than-normal occurrences of southerly flows associated with urban area emissions. However, the two intensive periods were characterized by northwesterly flow in the SF Bay Area (associated with relatively clean air). The onshore gradient was stronger than normal on most of the intensive days, causing ozone and precursor emissions from the SF Bay Area and the Broader Sac to be carried into the Sierra foothills. On other intensive days, air flow patterns either carried SF Bay Area emissions to the San Joaquin Valley or prevented those emissions from reaching the Upper Sac because of a persistent convergence zone near Sutter Buttes.

5. STATISTICAL ANALYSIS OF OZONE AND METEOROLOGICAL DATA

The purpose of this section is to describe certain pilot analyses of surface ozone and meteorological data collected during the summer of 1990. These pilot analyses were carried out to evaluate the efficacy of various data analysis procedures designed to quantify the frequency and magnitude of transport of ozone and precursor pollutants into the Upper Sacramento Valley (Upper Sac) from the Broader Sacramento Area (Broader Sac). Procedures which show promise in achieving this objective can then be applied to ozone and meteorological data collected over a number of years in other areas of the state, in order to more fully characterize transport between air basins.

Evaluation of transport from analyses of ozone concentration data is complicated by the confounding effects of meteorological conditions. In other words, ozone concentrations in the Upper Sac may be correlated with those in the Broader Sac simply because weather conditions conducive to ozone formation from local emissions tend to occur simultaneously in both the northern and southern ends of the valley. Unfortunately, it is conceivable that wind patterns favorable to transport may occur primarily in conjunction with these same conditions, thus further complicating the situation. These issues are discussed here in the context of three different analysis approaches: (1) analysis of diurnal ozone concentration patterns, (2) site-to-site ozone concentration correlations, and (3) stepwise regression of ozone at selected receptor sites against meteorological variables and ozone concentrations at other locations.

5.1 DIURNAL OZONE CONCENTRATION PATTERNS

Relatively high ozone concentrations in the Upper Sac is a necessary, but not sufficient, condition for a significant contribution to ozone exceedances by transport into the Upper Sac. Based on this hypothesis, a group of "potential transport days" was identified as consisting of all 1990 days on which daily maximum ozone concentrations at Redding, Red Bluff, or Chico exceeded 9.5 pphm. Days meeting this criterion are listed in Table 5-1.

Diurnal profiles of hourly ozone concentrations averaged over all potential transport days were prepared for selected sites and compared with similar plots for days not in the potential transport group (see Figures 5-1 through 5-14). As indicated in Table 5-2, diurnal patterns for potential transport days at Burney and Yuba City (near North Yuba) are unlikely to be representative of such days due to insufficient data.

If significant transport is taking place on a regular basis on potential transport days but not on other days, we would expect to see differences in the diurnal patterns between the two groups. A review of the plots in Figures 5-1 through 5-14 reveals no obvious differences in the timing or number of peaks although there is some evidence for a second late-afternoon peak on potential transport days at Yuba City. Examination of the plots reveals that the only consistent distinguishing feature of the potential transport days is that concentrations are higher at all hours, with maximum differences at the time of the afternoon peak (except at Red Bluff and Sutter

Table 5-1. Dates of potential transport (i.e., with daily maximum ozone > = 9.5 pphm) at Redding, Chico, or Red Bluff.

Obs No.	Date	Max O_3	Site
1	900621	12.0	Redding
2	900708	10.0	Red Bluff
3	900709	10.0	Red Bluff
4	900710	10.0	Redding
5	900710	11.0	Red Bluff
6	900712	12.0	Red Bluff
7	900714	10.0	Red Bluff
8	900715	11.0	Redding
9	900717	11.0	Red Bluff
10	900728	10.0	Redding
11	900728	10.0	Red Bluff
12	900729	11.0	Redding
13	900730	11.0	Redding
14	900803	10.0	Redding
15	900804	11.0	Redding
16	900804	11.0	Red Bluff
17	900805	10.0	Redding
18	900805	10.0	Red Bluff
19	900806	10.0	Red Bluff
20	900807	13.0	Redding
21	900808	12.0	Chico
22	900809	13.0	Chico
23	900810	10.0	Redding
24	900812	10.0	Redding
25	900813	11.0	Redding

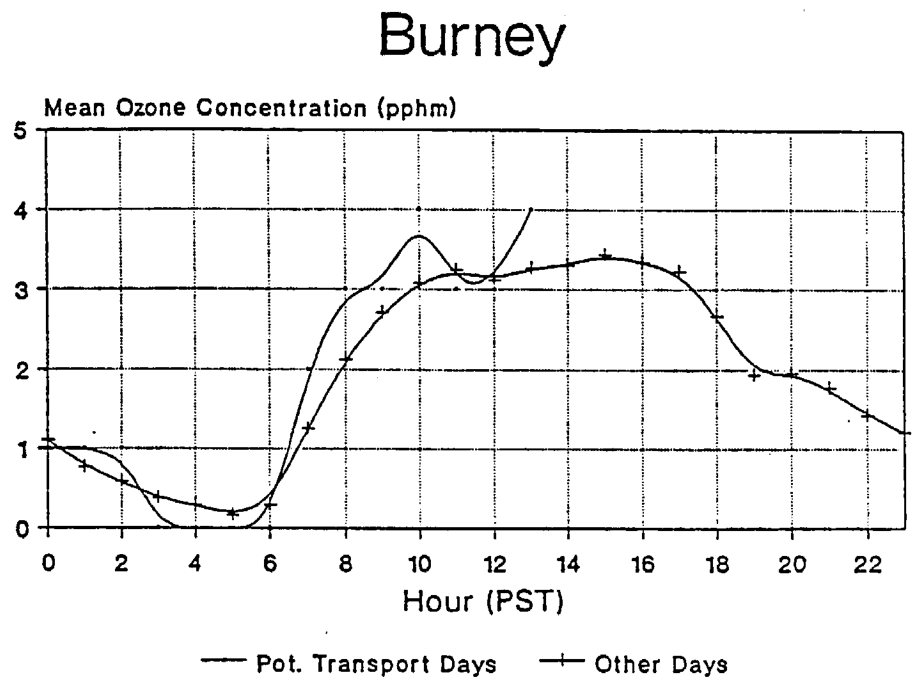


Figure 5-1. Diurnal profiles of hourly ozone concentrations averaged over all potential transport days for Burney compared with similar plots for days not in the potential transport group.

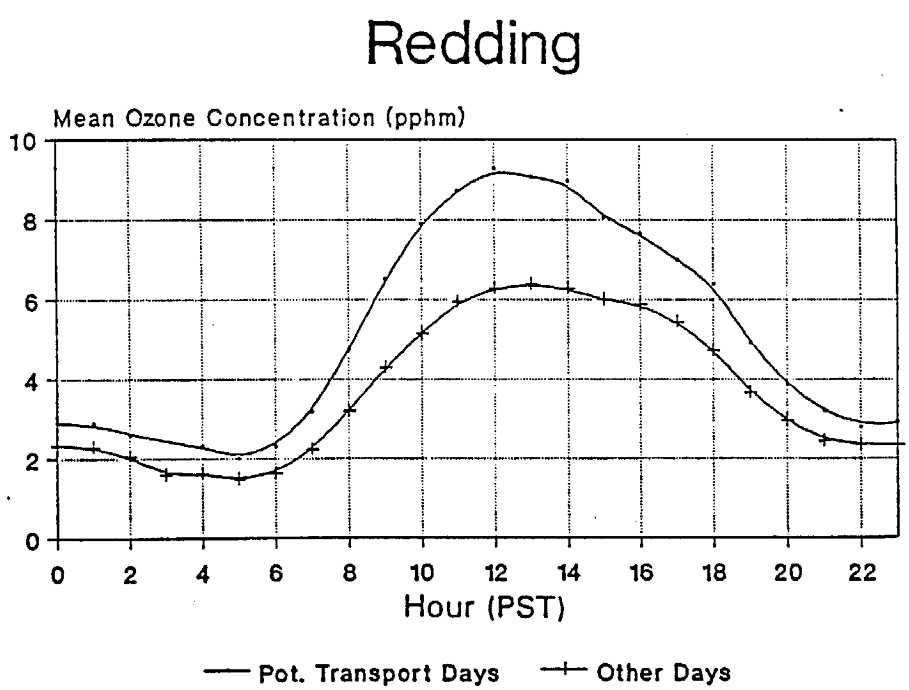


Figure 5-2. Diurnal profiles of hourly ozone concentrations averaged over all potential transport days for Redding compared with similar plots for days not in the potential transport group.

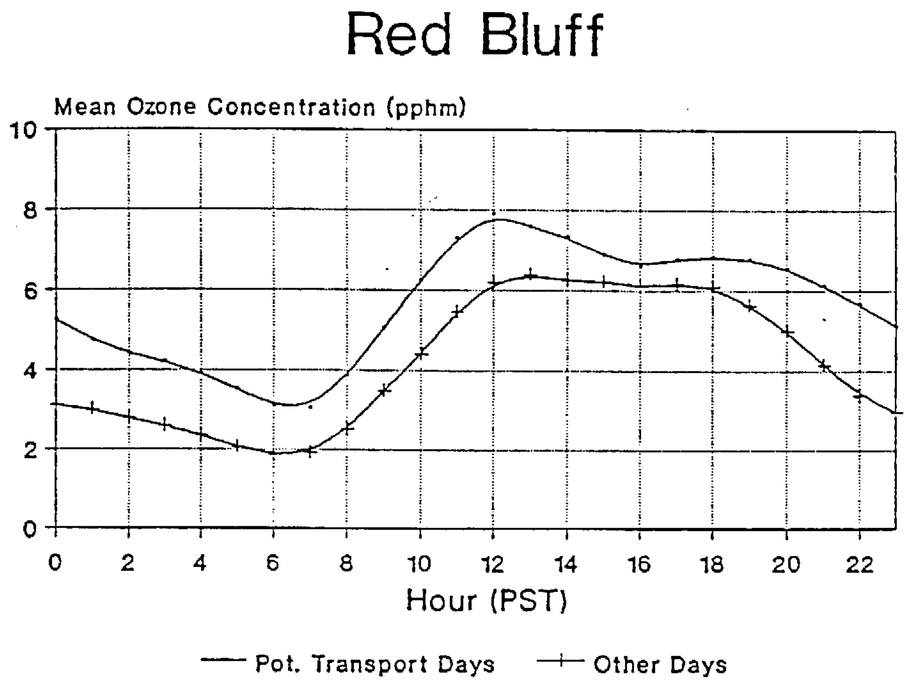


Figure 5-3. Diurnal profiles of hourly ozone concentrations averaged over all potential transport days for Red Bluff compared with similar plots for days not in the potential transport group.

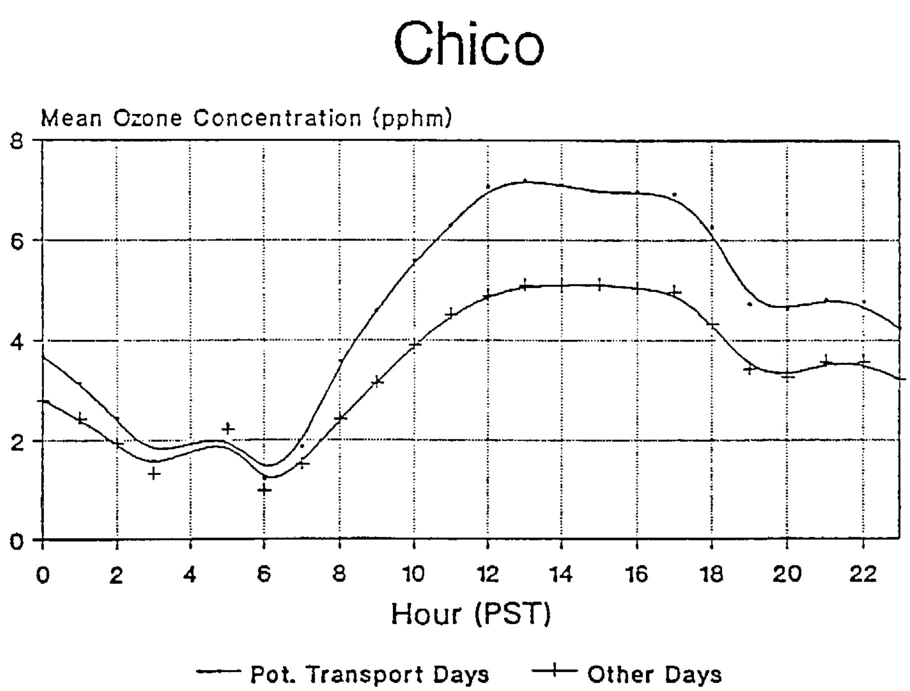


Figure 5-4. Diurnal profiles of hourly ozone concentrations averaged over all potential transport days for Chico compared with similar plots for days not in the potential transport group.

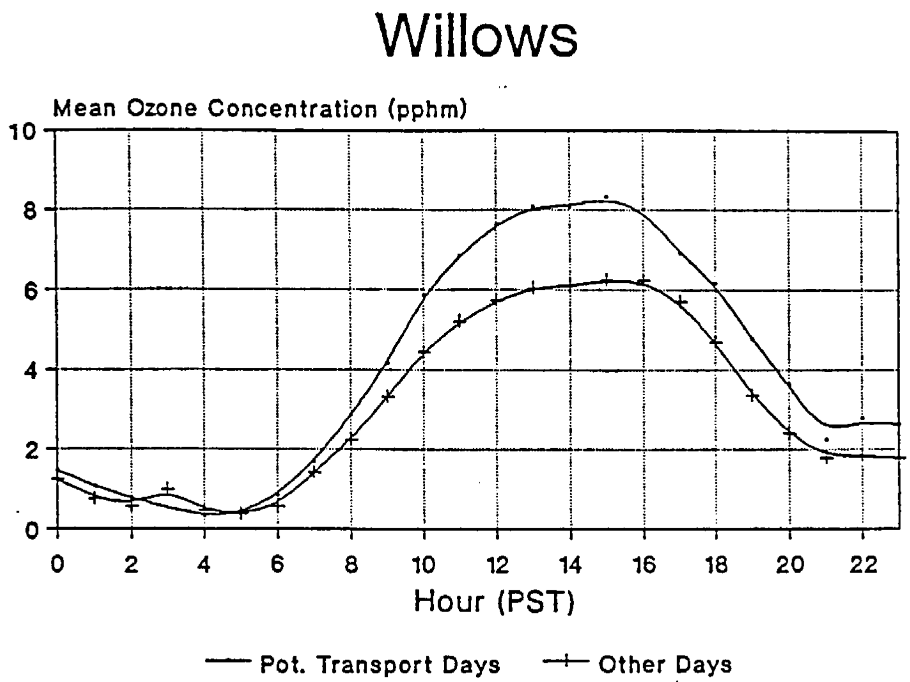


Figure 5-5. Diurnal profiles of hourly ozone concentrations averaged over all potential transport days for Willows compared with similar plots for days not in the potential transport group.

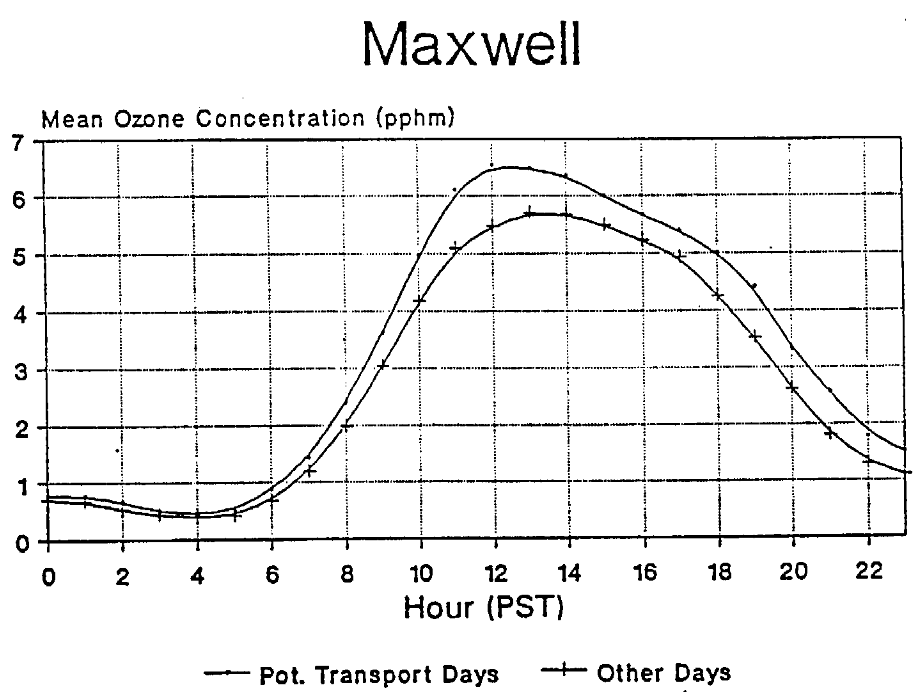


Figure 5-6. Diurnal profiles of hourly ozone concentrations averaged over all potential transport days for Maxwell compared with similar plots for days not in the potential transport group.

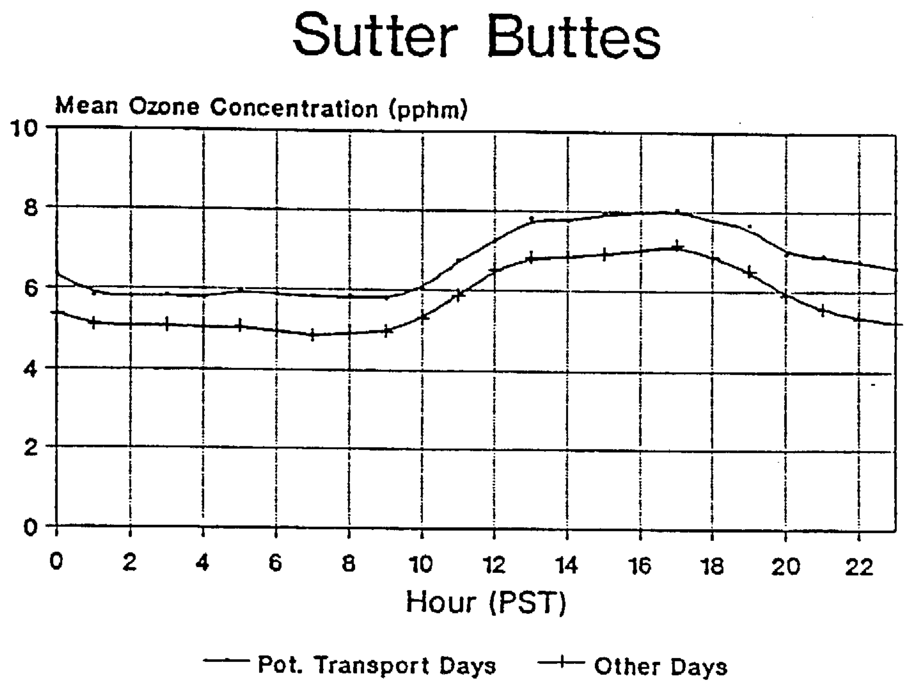


Figure 5-7. Diurnal profiles of hourly ozone concentrations averaged over all potential transport days for Sutter Buttes compared with similar plots for days not in the potential transport group.

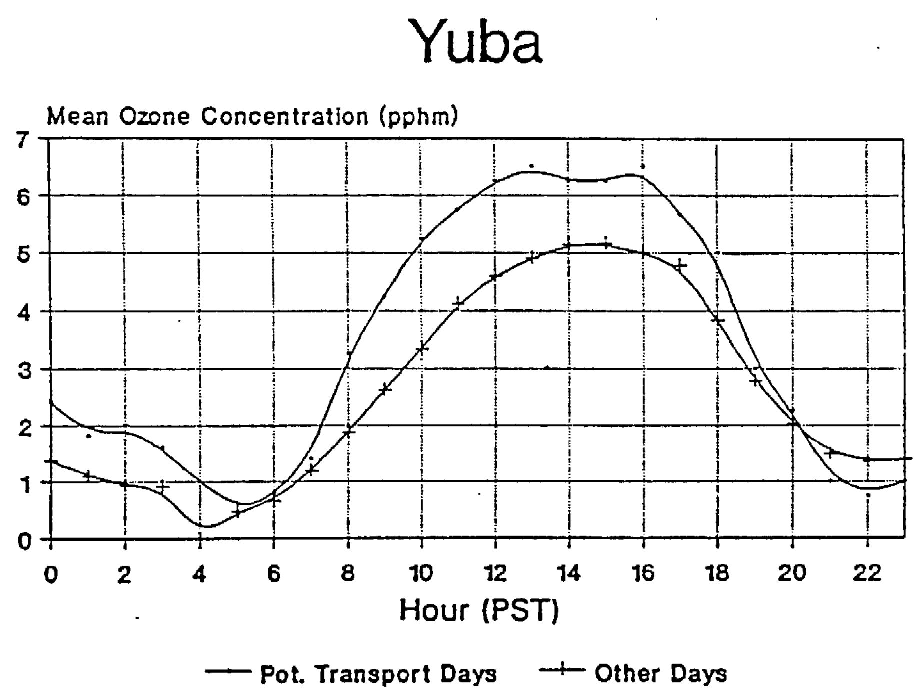


Figure 5-8. Diurnal profiles of hourly ozone concentrations averaged over all potential transport days for Yuba City compared with similar plots for days not in the potential transport group.

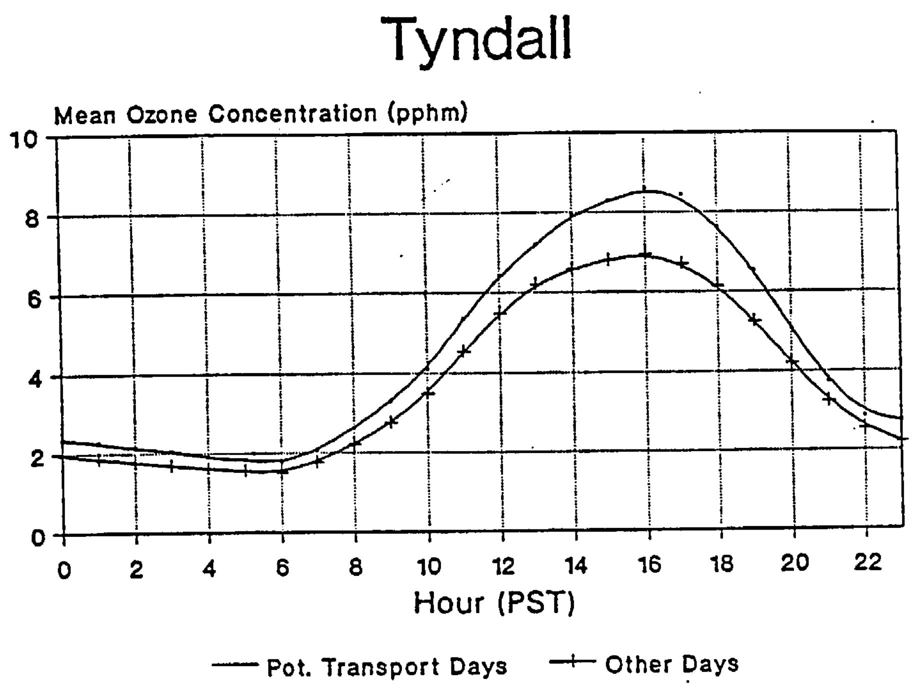


Figure 5-9. Diurnal profiles of hourly ozone concentrations averaged over all potential transport days for Tyndall compared with similar plots for days not in the potential transport group.

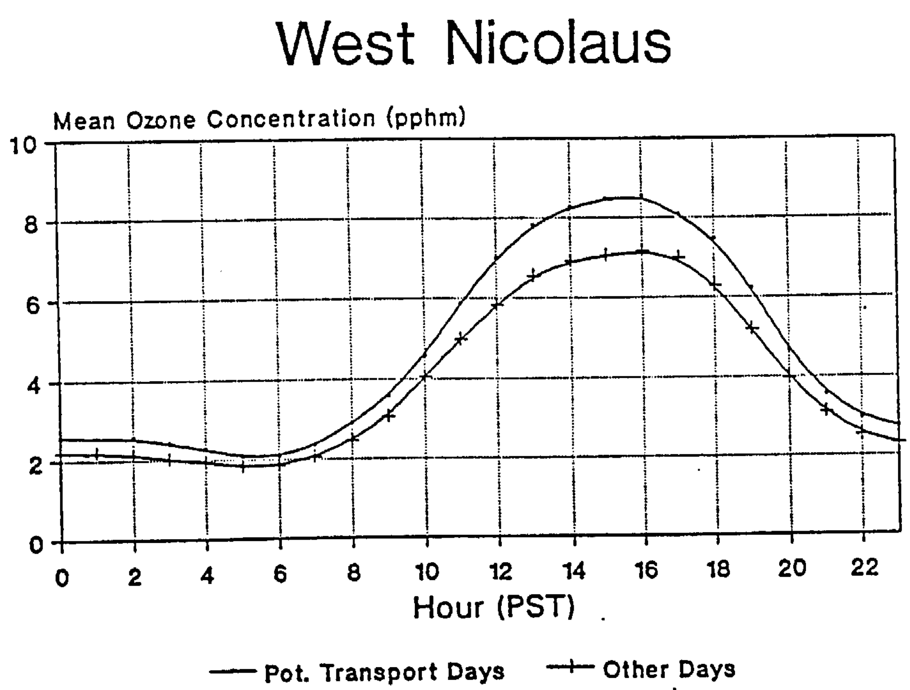


Figure 5-10. Diurnal profiles of hourly ozone concentrations averaged over all potential transport days for West Nicolaus compared with similar plots for days not in the potential transport group.

Pleasant Grove

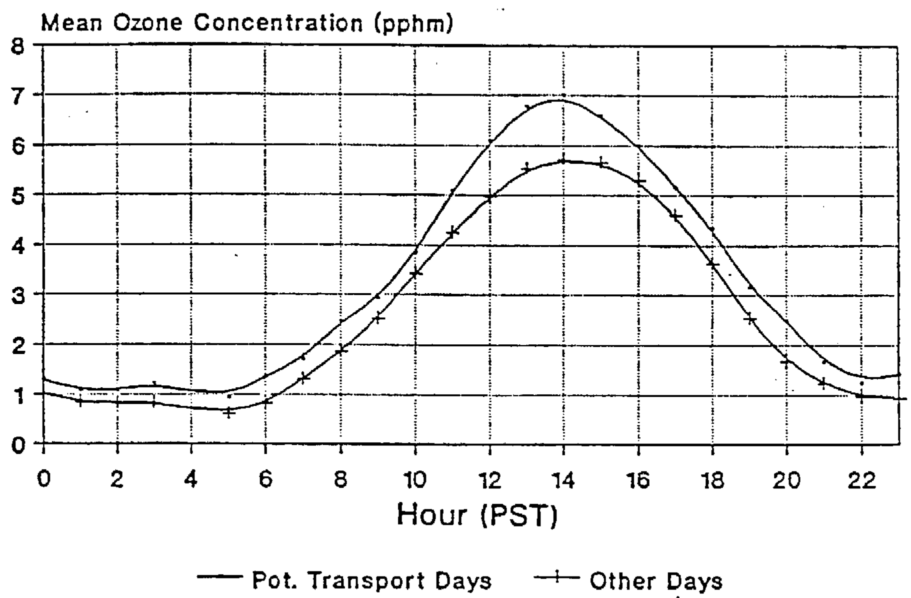


Figure 5-11. Diurnal profiles of hourly ozone concentrations averaged over all potential transport days for Pleasant Grove compared with similar plots for days not in the potential transport group.

North Highlands

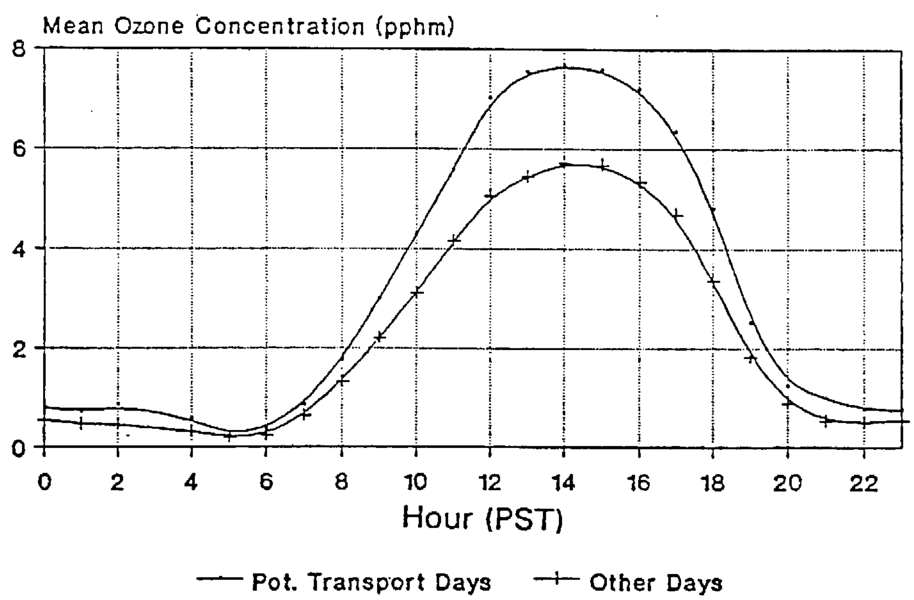


Figure 5-12. Diurnal profiles of hourly ozone concentrations averaged over all potential transport days for North Highlands compared with similar plots for days not in the potential transport group.

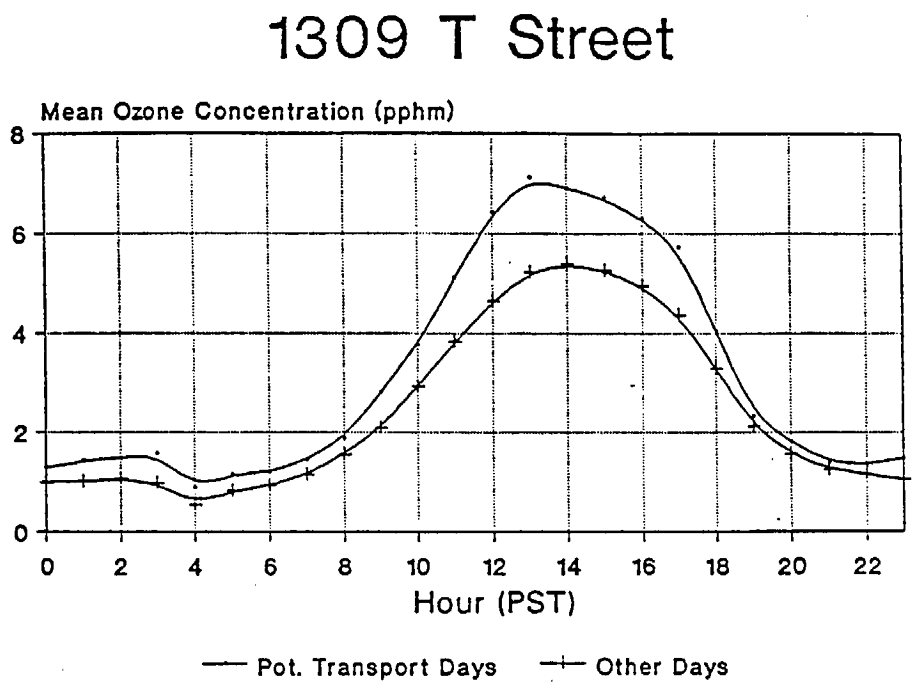


Figure 5-13. Diurnal profiles of hourly ozone concentrations averaged over all potential transport days for 1309 T Street compared with similar plots for days not in the potential transport group.

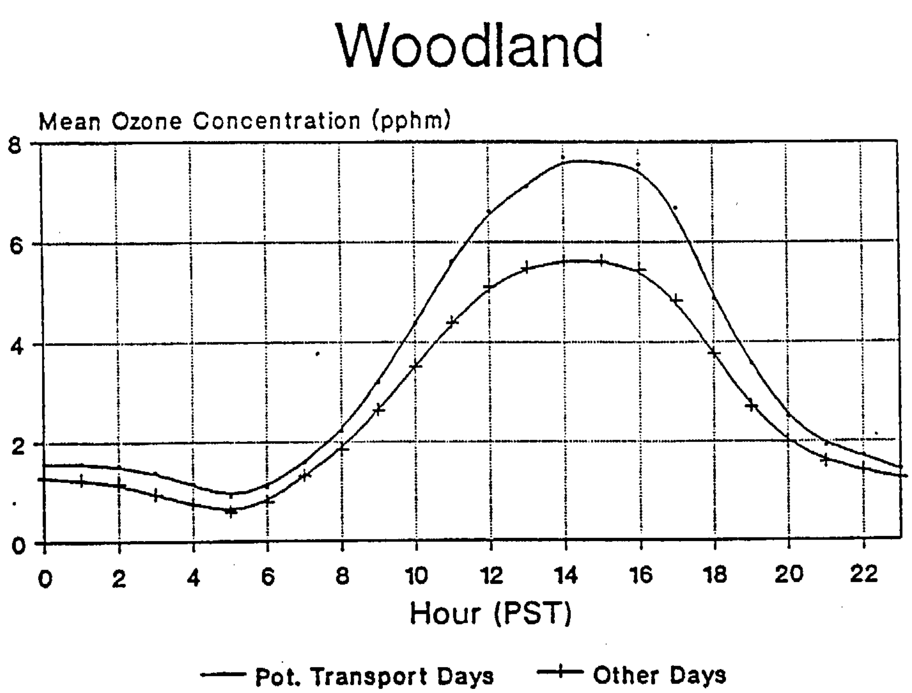


Figure 5-14. Diurnal profiles of hourly ozone concentrations averaged over all potential transport days for Woodland compared with similar plots for days not in the potential transport group.

Table 5-2. Number of non-missing hourly ozone values (12:00 to 18:00 PST) on 1990 potential transport days (see Table 5-1) by site and transport category.

Site	Abbreviation Used in Tables 5-3 and 5-5	Transport Category	No. Values
1309T	THT	Pot. Trans	20
1309T		Other	120
N. Highlands	NHL	Pot. Trans	21
N. Highlands		Other	121
Burney	BUR	Pot. Trans	<1
Burney		Other	50
Chico	CMZ	Pot. Trans	21
Chico		Other	117
Maxwell	MAX	Pot. Trans	18
Maxwell		Other	66
Pleasant Grove	PLG	Pot. Trans	12
Pleasant Grove		Other	106
Redding	RED	Pot. Trans	20
Redding		Other	116
Sutter Buttes	STB	Pot. Trans	20
Sutter Buttes		Other	60
Tyndall	TYN	Pot. Trans	21
Tyndall		Other	86
W. Nicolaus	WNC	Pot. Trans	21
W. Nicolaus		Other	86
Willows	WIL	Pot. Trans	13
Willows		Other	69
Woodland	WOD	Pot. Trans	21
Woodland		Other	121
Yuba City	YBA	Pot. Trans	4
Yuba City		Other	86
Red Bluff	REB	Pot. Trans	19
Red Bluff		Other	83

Buttes). This also holds for sites in Sacramento, confirming that Sacramento ozone concentrations tend to be high at the same time that concentrations in the northern end of the valley are high, and suggests that high ozone concentrations in the northern end of the Sacramento Valley are not a reliable indicator of transport. The failure of this approach to be a reliable indicator of transport may in part be because weather patterns conducive to ozone formation from local emissions tend to occur simultaneously in both the Upper Sac and the Broader Sac.

However, there are significant and revealing differences in the diurnal patterns from one site to the next. In particular, while sites within and close to Sacramento (1309 T St., Pleasant Grove, North Highlands) peak at or before approximately 1400 PST, the time of the daily maximum concentration at Tyndall, West Nicolaus, and Yuba City extends until approximately 1500 PST to 1600 PST, suggesting that these sites are affected by same day transport from Sacramento. Concentrations at Maxwell, while not high, peak early in the day (1200 PST to 1300 PST). This indicates ozone production from local sources, occasional entrainment of ozone held aloft overnight into the mixed layer, and/or overnight transport of precursors into the area. Redding exhibits a similar pattern, but with a more pronounced early afternoon maximum. The pattern at Chico is quite different from these, with lower concentrations than at Willows and a broad afternoon peak. The site-to-site differences in the diurnal ozone plots seen in this study of the summer of 1990 ozone data is consistent with the analysis of Roberts et al. (1992). In that study, diurnal ozone plots were prepared from all available data during 1980-1989. Roberts et al. (1992) found ozone temporal patterns including timing of the ozone peak which closely match those of this analysis.

5.2 CORRELATION ANALYSIS

Linear correlation coefficients were calculated between the daily maximum ozone concentrations at each monitoring site and the daily maximum concentration averaged over five highly correlated sites in Sacramento (Del Paso, 1309 T St., Citrus Heights, North Highlands, and Folsom; see correlation coefficients in Table 5-3). Correlations were calculated with a zero, 1-, and 2-day lag in the Sacramento concentrations. Results are summarized in Table 5-4. High correlations (e.g., 0.75 and higher) with same day Sacramento concentrations are observed at Pleasant Grove, Tyndall, West Nicolaus, Woodland, and Yuba City, suggesting that these stations are within the same-day sphere of influence of Sacramento. All zero and 1-day lag coefficients are significant at the 99.9 percent level (assuming independent observations; actual significance levels are lower due to autocorrelation). At Redding, Red Bluff, Chico, and Willows, the 1-day lag correlation coefficients are nearly as big as or bigger than the zero lag correlation coefficients, suggesting that these sites are outside of the immediate sphere of influence of Sacramento but may be affected by occasional second day or overnight transport. Maxwell appears to be an intermediate site between these two regimes.

Table 5-3. Station correlations for Sacramento ozone sites: Pearson correlation coefficients / Prob > |R| under Ho: Rho=0 / number of observations.

	DPMMAXO	THTMAXO	SRSMAXO	NHLMAXO	FOLMAXO
DPMMAXO	1.00000 0.0 122	0.90179 0.0001 122	0.87069 0.0001 122	0.90277 0.0001 122	0.83126 0.0001 118
THTMAXO	0.90179 0.0001 122	1.00000 0.0 122	0.80071 0.0001 122	0.85565 0.0001 122	0.78165 0.0001 118
SRSMAXO	0.87069 0.0001 122	0.80071 0.0001 122	1.00000 0.0 122	0.90184 0.0001 122	0.90325 0.0001 118
NHLMAXO	0.90277 0.0001 122	0.85565 0.0001 122	0.90184 0.0001 122	1.00000 0.0 122	0.84639 0.0001 118
FOLMAXO	0.83126 0.0001 118	0.78165 0.0001 118	0.90325 0.0001 118	0.84639 0.0001 118	1.00000 0.0 118

Where:

MAXO = daily maximum ozone concentration
DPM = Del Paso Manor
THT = 13th and T (Sacramento)
SRS = Citrus Heights - Sunrise
NHL = North Highlands
FOL = Folsom

Table 5-4. Correlation of daily maximum ozone concentrations: Pearson correlation coefficients / Prob > |R| under Ho: Rho=0 / number of observations.

	SACMAX0	SACMAX1	SACMAX2	BURMAX	CMZMAX	MAXMAX	PLGMAX0	REDMAX0	REBMAX0	STBMAX0	TYNMAX0	WNCMAX	WILMAX0	WODMAX	YBAMAX0
SACMAX0	1.00000	0.48205	0.42920	0.02155	0.68176	0.69290	0.81901	0.54819	0.61457	0.69707	0.85593	0.83667	0.69593	0.87173	0.74767
	0.0000	0.0001	0.0001	0.8896	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
	118	117	116	44	112	65	100	111	78	59	85	85	65	117	82
SACMAX1	0.48205	1.00000	0.48205	0.45164	0.73433	0.59018	0.34085	0.58649	0.55384	0.49156	0.59286	0.49507	0.68846	0.61469	0.46050
	0.0001	0.0000	0.0001	0.0018	0.0001	0.0001	0.0005	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
	117	118	117	45	112	65	101	111	79	59	85	85	66	117	82
SACMAX2	0.42920	0.48205	1.00000	0.41675	0.60986	0.50332	0.26947	0.53032	0.42429	0.45895	0.47114	0.36524	0.59580	0.49078	0.27015
	0.0001	0.0001	0.0000	0.0040	0.0001	0.0001	0.0062	0.0001	0.0001	0.0003	0.0001	0.0006	0.0001	0.0001	0.0141
	116	117	118	46	112	65	102	111	80	59	85	85	67	117	82

Where:

MAX0 = daily maximum ozone concentration
MAX1 = daily maximum ozone concentration, 1-day lag
MAX2 = daily maximum ozone concentration, 2-day lag
SAC = Sacramento
BUR = Burney
CMZ = Chico
MAX = Maxwell
PLG = Pleasant Grove
RED = Redding
REB = Red Bluff
STB = Sutter Buttes
TYN = Tyndall
WNC = W. Nicolas
WIL = Willows
WOD = Woodland
YBA = Yuba City

5.3 STEP-WISE REGRESSION ANALYSIS

A step-wise regression analysis was performed in an attempt to sort out the major influences on the Upper Sac ozone concentrations. Daily maximum ozone concentrations at selected sites were regressed against zero, 1-, and 2-day lagged Sacramento ozone concentrations (SACMAX0, SACMAX1, and SACMAX2, respectively) and the daily maximum temperature at Redding (REDDTEMP) and Sacramento (1309 T St.: THTTEMP). Results of the analysis are summarized in Tables 5-5 and 5-6.

Table 5-5 summarizes the results of the first step of the regression procedure (i.e., the results of regressing against one independent variable (SACMAX0, SACMAX1, SACMAX2, REDDTEMP, or THTTEMP) at a time). All of the simple regression models thus formed are significant at the 95 percent confidence level (except predictions at Yuba City using SACMAX2). No single regressor accounts for more than 50 percent of the variance in daily maximum ozone at either Redding or Red Bluff. At these sites, the daily maximum temperature at Redding is the single most important variable. REDDTEMP also accounts for over three-fourths of the variance at Willows. In contrast, ozone concentrations at Yuba City and West Nicolaus are more closely related to same-day concentrations at Sacramento than to either of the temperature variables. Chico represents an intermediate site, where both temperature at Redding and previous-day ozone at Sacramento are influential.

Table 5-6 summarizes the results of the remaining steps in the stepwise regressions. Examination of the increase in model R-square statistics for Redding, Red Bluff, and Willows as additional variables are entered indicates that, after the Redding temperature effect is accounted for, all of the other regressors are approximately equal in their ability to account for the remaining variance, and inclusion of these variables in the regression does not add appreciably to the total variance accounted for. Thus, local weather conditions are slightly better predictors of ozone in the Upper Sac than are Sacramento ozone concentrations on the same or previous days. No transport effects are readily apparent in the results for these sites.

At Yuba City and West Nicolaus, after the same-day maximum ozone concentration at Sacramento is accounted for, none of the other regressors (including the temperature variables) contribute significantly to the total R-square. This suggests that these sites are heavily influenced by transport from Sacramento. At Chico, after the effect of temperature variations at Redding are accounted for, the previous day's ozone concentration at Sacramento contributes another 7 percent to the total R-square. This additional effect associated with events in Sacramento the day before suggests that Chico, though too far north to experience same day transport from Sacramento, may be influenced by overnight transport.

5.4 CONCLUSIONS

Although the statistical techniques used in these pilot analyses were not fully successful in quantifying ozone and precursor transport from the

Table 5-5. Summary of simple linear regression for daily maximum ozone at selected sites for each candidate regression variable defined as follows:

RDDTEMP: Redding daily maximum temperature
THHTEMP: Sacramento (13th and T St) daily maximum temperature
SACMAX0: Sacramento daily maximum ozone concentration
SACMAX1: Sacramento daily maximum ozone at lag 1 day
SACMAX2: Sacramento daily maximum ozone at lag 2 days

	Variable	Tolerance	Model R**2	F	Prob>F
Redding					
	SACMAX0	1.000000	0.3151	25.7620	0.0001
	SACMAX1	1.000000	0.3144	25.6758	0.0001
	SACMAX2	1.000000	0.2130	15.1574	0.0003
	RDDTEMP	1.000000	0.4264	41.6267	0.0001
	THTTEMP	1.000000	0.3159	25.8543	0.0001
Red Bluff					
	SACMAX0	1.000000	0.3905	29.4687	0.0001
	SACMAX1	1.000000	0.2263	13.4564	0.0006
	SACMAX2	1.000000	0.1561	8.5068	0.0055
	RDDTEMP	1.000000	0.4123	32.2779	0.0001
	THTTEMP	1.000000	0.3698	26.9944	0.0001
Chico					
	SACMAX0	1.000000	0.4860	53.8954	0.0001
	SACMAX1	1.000000	0.6028	86.5117	0.0001
	SACMAX2	1.000000	0.3886	36.2355	0.0001
	RDDTEMP	1.000000	0.6308	97.3793	0.0001
	THTTEMP	1.000000	0.4873	54.1694	0.0001
Willows					
	SACMAX0	1.000000	0.5942	51.2393	0.0001
	SACMAX1	1.000000	0.5495	42.6903	0.0001
	SACMAX2	1.000000	0.4755	31.7273	0.0001
	RDDTEMP	1.000000	0.7649	113.8531	0.0001
	THTTEMP	1.000000	0.5710	46.5868	0.0001
North Yuba					
	SACMAX0	1.000000	0.6944	68.1783	0.0001
	SACMAX1	1.000000	0.3529	16.3605	0.0003
	SACMAX2	1.000000	0.0748	2.4268	0.1298
	RDDTEMP	1.000000	0.5343	34.4253	0.0001
	THTTEMP	1.000000	0.5006	30.0718	0.0001
West Nicolaus					
	SACMAX0	1.000000	0.7040	147.4368	0.0001
	SACMAX1	1.000000	0.3314	30.7318	0.0001
	SACMAX2	1.000000	0.1714	12.8229	0.0007
	RDDTEMP	1.000000	0.6063	95.4904	0.0001
	THTTEMP	1.000000	0.4790	57.0109	0.0001

Table 5-6. Summary of forward step-wise regression analysis using daily maximum ozone as the dependent variable and regressors defined as follows:

RDDTEMP: Redding daily maximum temperature
THHTEMP: Sacramento (13th and T St) daily maximum temperature
SACMAX0: Sacramento daily maximum ozone concentration
SACMAX1: Sacramento daily maximum ozone at lag 1 day
SACMAX2: Sacramento daily maximum ozone at lag 2 days

Step	Variable Entered	Number In	Partial R**2	Model R**2	C(p)	F	Prob>F
Redding							
1	RDDTEMP	1	0.4264	0.4264	1.3519	41.6267	0.0001
2	SACMAX1	2	0.0156	0.4420	1.8472	1.5370	0.2203
3	SACMAX2	3	0.0119	0.4539	2.6991	1.1764	0.2829
4	SACMAX0	4	0.0066	0.4605	4.0607	0.6499	0.4238
Red Bluff							
1	RDDTEMP	1	0.4123	0.4123	0.7995	32.2779	0.0001
2	SACMAX0	2	0.0327	0.4451	0.3048	2.6537	0.1103
Chico							
1	RDDTEMP	1	0.6308	0.6308	23.2949	97.3793	0.0001
2	SACMAX1	2	0.0703	0.7011	10.3777	13.1807	0.0006
3	SACMAX2	3	0.0304	0.7315	5.9342	6.2246	0.0156
4	SACMAX0	4	0.0185	0.7501	4.0014	4.0068	0.0504
Willows							
1	RDDTEMP	1	0.7649	0.7649	4.0134	113.8531	0.0001
2	SACMAX2	2	0.0183	0.7832	3.1335	2.8686	0.0995
3	THTTEMP	3	0.0067	0.7899	4.0727	1.0584	0.3111
4	SACMAX0	4	0.0085	0.7984	4.7337	1.3503	0.2538
5	SACMAX1	5	0.0047	0.8031	6.0000	0.7337	0.3983
North Yuba							
1	SACMAX0	1	0.6944	0.6944	3.2500	68.1783	0.0001
2	SACMAX1	2	0.0363	0.7308	1.5345	3.9132	0.0575
West Nicolaus							
1	SACMAX0	1	0.7040	0.7040	5.4185	147.4368	0.0001
2	RDDTEMP	2	0.0214	0.7254	2.6864	4.7565	0.0331
3	THTTEMP	3	0.0099	0.7353	2.5042	2.2380	0.1399
4	SACMAX1	4	0.0022	0.7374	4.0269	0.4853	0.4888

Broader Sac to the Upper Sac, they were helpful in reaching the following conclusions regarding ozone transport:

- Examination of diurnal ozone concentrations failed to show that the timing of ozone peaks on high ozone days was a useful tool on days thought to be potential transport days. This failure was likely due to two major issues: (1) ozone concentrations in the Upper Sac may be correlated with those in the Broader Sac simply because weather conditions conducive to ozone formation from local emissions tend to occur simultaneously in both the northern and southern ends of the valley; and (2) it is conceivable that wind patterns favorable to transport may occur primarily in conjunction with these same conditions, thus further complicating the situation.

- Examination of diurnal ozone concentrations did show that the timing of ozone peaks on all high ozone days was a useful tool for distinguishing sites influenced by same-day transport from sites where ozone results from other sources. These other sources could include ozone produced from local precursor emissions, ozone held aloft overnight entrained into the mixed layer, and overnight transport of precursor emissions. This approach suggests that Tyndall, West Nicolaus, and Yuba City were likely affected by same-day transport from Sacramento; Redding was not likely to be affected by same-day transport from Sacramento; and Chico was potentially affected by same-day transport from Sacramento.

- Correlation analysis of daily maximum ozone concentrations showed that Redding, Red Bluff, Chico, and Willows were not likely to be influenced by same day transport from Sacramento; sites as close to Sacramento as Yuba City and Woodland were likely to be influenced by same day transport from Sacramento; and Maxwell appeared to be somewhere between these two regimes.

- Step-wise regression analysis of daily maximum ozone concentrations also showed that Redding, Red Bluff, and Willows were not likely to be influenced by same day transport from Sacramento; sites as close to Sacramento as Yuba City and Woodland are likely to be influenced by same day transport from Sacramento; and Chico may be influenced by overnight transport from Sacramento.

In summary, the timing of ozone peaks, correlations using daily maximum ozone concentrations, and step-wise regression of daily maximum ozone concentrations showed that same-day transport from the Broader Sac likely influenced Tyndall, West Nicolaus, Yuba City, and Woodland and was unlikely to influence Redding, Red Bluff, and Willows. The analyses showed mixed results for Maxwell and Chico. These analysis results qualitatively help to make transport assessments more reliable, but did not quantify transport contributions.

In future studies, it may be possible to extend these methods and combine them with other methods to provide quantitative estimates of the influence of transported material on downwind concentrations. For example, trends in upwind source region precursor emissions could be compared with emission and concentration trends at downwind receptor regions. For small (but statistically significant) changes in emissions, a regression model may provide an adequate fit to the data and allow one to estimate the relative contribution of upwind emissions to downwind ozone concentrations.

6. PRECURSOR CONTRIBUTION ESTIMATES USING TRAJECTORY METHODS

This section presents the analysis results for air-parcel trajectories and precursor contributions for the Upper Sacramento Valley (Upper Sac). Note that the work reported in this section was performed jointly under two different ARB contracts; additional information on these methods and the characteristics of pollutant transport to the Upper Sac are available in Roberts et al. (1992).

6.1 TRANSPORT-PATH ANALYSES

This subsection is divided into three parts. The first summarizes the general methods that were used to identify transport paths. The second and third parts summarize the results of our trajectory analyses and discusses those results using surface and aloft data, respectively. The purposes of these analyses are to evaluate if transport takes place, how often it occurs, and to estimate the general path of pollutant transport to the Upper Sac.

6.1.1 Summary of Trajectory Methods

During our determination of potential transport paths, we performed the following tasks in succession:

- Performed an analysis and review of past field, data analysis, and modeling studies in the area. We used this review to identify potential transport paths to the downwind air basin.

- Acquired wind speed and wind direction data to cover the potential transport paths from the upwind air basin(s) to the downwind air basin; evaluated the data for appropriateness for subsequent analyses. On most of the days analyzed, only surface wind data were available. In a few cases, sufficient upper-air wind data were also available.

- Generated hourly wind fields for the periods of interest and used the wind fields to calculate air-parcel trajectories. If upper-air data were available, we also prepared aloft wind fields and trajectories. Backward air-parcel trajectories were calculated for periods of high ozone concentrations at receptor sites. These trajectories were used to determine the general path that an arriving air parcel might have followed on its way to the receptor monitoring site. We also calculated some forward trajectories for periods of high emissions in the potential source areas. These trajectories were used to determine the general path that a polluted air parcel might have followed on its way from the source area.

- Prepared a consensus of the trajectory analysis for each receptor of interest. We used the individual results of a large number of backward and forward trajectories to develop the consensus trajectory (or trajectories) for each receptor. Rather than use an individual trajectory for one exceedance day, we developed this consensus using many trajectories to increase the probability that the correct transport path would be represented.

To develop hourly wind fields for violation days, we used the Caltech 2-D wind interpolation procedure, as modified and documented by Dr. Kit Wagner of the Technical Support Division of the California Air Resources Board (ARB). For surface wind fields, the procedure used hourly averaged wind speed and direction data from a large number of surface monitoring sites, including data collected as part of this study and the following additional sources (in some cases the area or temporal coverage of the data is identified):

- The ARB;
- Weather Network, Inc. for the Sacramento Valley;
- The Sacramento Area Ozone Study (sponsored in the summers of 1989 and 1990 by the Sacramento Area Council of Governments);
- The Bay Area Air Quality Management District (BAAQMD) 10-meter tower network;
- The San Joaquin Valley Air Quality Study and AUSPEX (SJVAQS/AUSPEX) for the summer of 1990 (these data were still undergoing validation);
- The National Ocean Buoy Center for data collected offshore of northern California by the Minerals Management Service, the U.S. Coast Guard, the Army Corps of Engineers, and the National Weather Service (NWS); and
- The CIMIS network. Since these data are collected at about 2 meters, wind speeds are often slower than at higher altitudes; we only used CIMIS data from locations where other data were not available.

For a few days during 1989 and 1990, sufficient upper-air wind data were available to compute aloft wind fields for much of the Sacramento Valley area. For these days, we obtained upper-air wind speed and direction data for intensive sampling days from the following:

- The 1989 Sacramento Area Ozone Study: four soundings per day at seven sites (see Prins et al., 1990; and Prins and Prouty, 1990);
- The 1990 Sacramento Area Ozone Study: six soundings per day at four sites (see Prins and Prouty, 1991a and 1991b);
- Data collected in this study for the summer of 1990: four soundings per day at two sites (see Prins and Prouty, 1991c and 1991d); and
- The corresponding data from the NWS twice-daily soundings at the Oakland Airport.

All of the upper-air data were interpolated to each hour between soundings. We also used hourly data from two Doppler acoustic sounders operated for the 1990 SJVAQS/AUSPEX (these data were still undergoing validation).

The wind field procedure used a 10-km by 10-km grid which covered the area of interest, including the downwind receptor area and the upwind source area(s). The trajectories were generated using the hourly wind field at 30-minute time steps. Back trajectories were generated for peak ozone hours on selected ozone violation days at important monitoring sites in the Upper Sac. Ensembles of trajectories defined typical transport paths on violation days.

6.1.2 Trajectory Results Using Surface Data

To evaluate transport to the Upper Sac, we selected a domain which included the receptor sites in the Upper Sac and the two upwind air basins, the Broader Sacramento Area (Broader Sac) and the San Francisco Bay Area (SF Bay Area). We also included the northern part of the San Joaquin Valley in order to complete the wind flow patterns out of the SF Bay Area and into both the Sacramento and San Joaquin Valleys. We used wind data from 85 surface wind measurement sites. The sites are shown on the map in Figure 6-1 and listed with UTM coordinates in Appendix B. Data for a few of these sites are limited in duration, such as those sites operated for the SACOG field studies in 1989 and 1990.

We selected ozone exceedance days from the 1987-1990 period, based on days with the highest ozone concentrations at the Upper Sac monitoring sites, plus the availability of surface and aloft meteorological data. We prepared surface wind fields for the Northern California domain for 86 days, 34 in 1987, 17 in 1988, 24 in 1989, and 11 in 1990. We then estimated forward and backward trajectories for selected locations and times. We prepared a total of 1144 forward and backward surface trajectories. The following discussion illustrates the general characteristics of those trajectories and summarizes the transport results; some additional details are available in Roberts et al. (1992).

Figures 6-2 through 6-4 illustrate various characteristics of the Upper Sac trajectories. These trajectories are for 1987, the most recent year when many ozone exceedances were recorded in the Upper Sac. These trajectories were prepared using surface winds only; no aloft Sacramento Valley wind data are available to use for 1987 trajectories. If both surface and aloft trajectories were available, some of the conclusions discussed below might be modified. Some examples using both surface and aloft trajectories will be covered in the next subsection.

Figure 6-2 shows back trajectories from Redding, Red Bluff, and Chico for 1600 PST on June 26, 1987; the trajectories for 1200 and 1400 PST were similar. On that day, maximum ozone concentrations were 13 pphm at Redding and 10 pphm at Chico, the highest of the year. The exact location of the air parcel history is inaccurate when the wind speeds are low, as in these examples. However, the general conclusion is still valid: that the air parcels were in the local area for the previous day or two.

Figure 6-3 shows back trajectories from Redding, Red Bluff, and Chico for 1200 PST on July 14, 1987 and on July 15, 1987; the trajectories for 1400 and 1600 PST on each day were similar to the ones shown. The maximum ozone concentrations on those days were 11 and 10 pphm, respectively at Redding, and

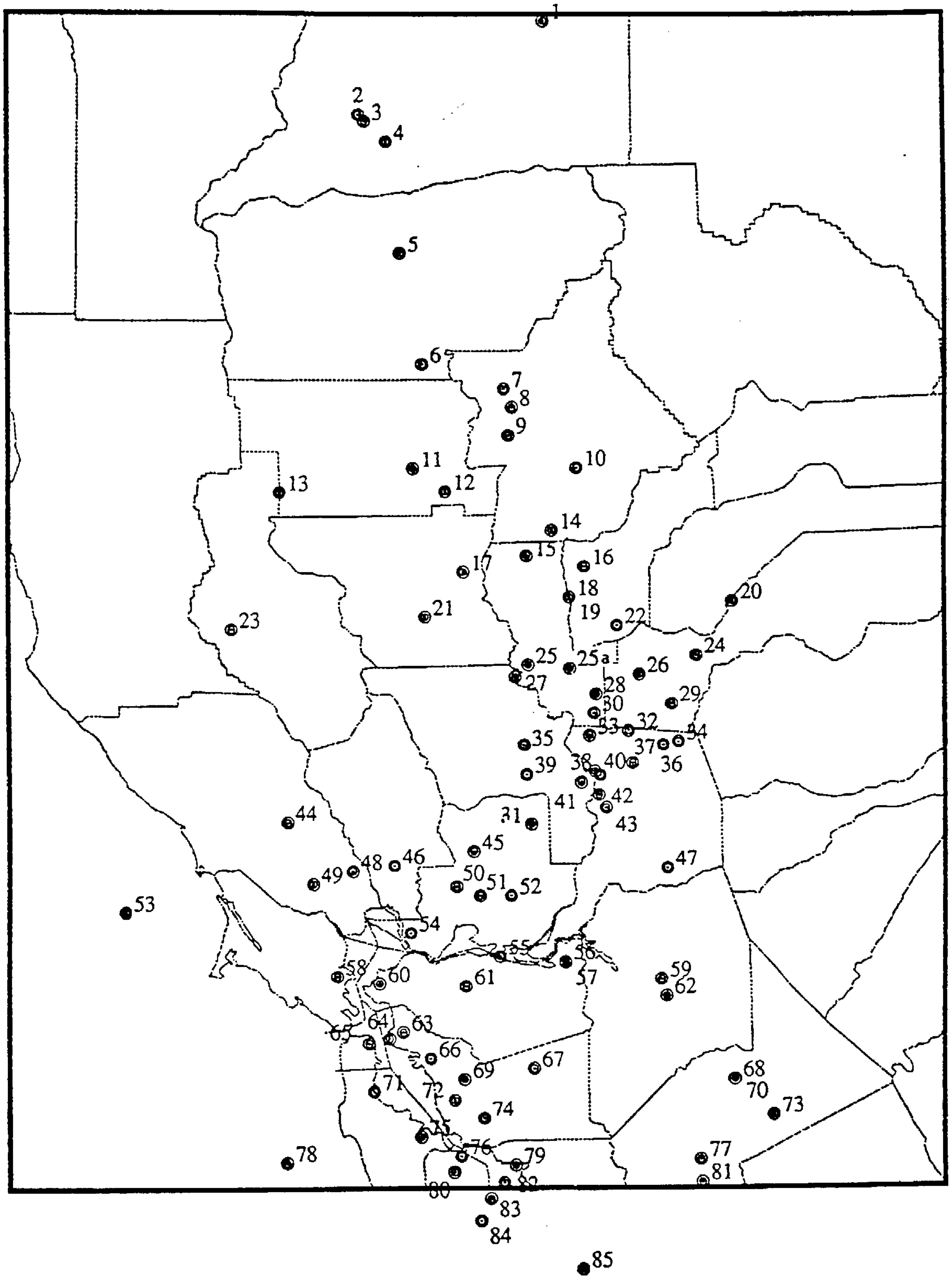


Figure 6-1. Map showing surface wind sites for Upper Sacramento Valley trajectories. (See Appendix B for the site names and UTM coordinates.

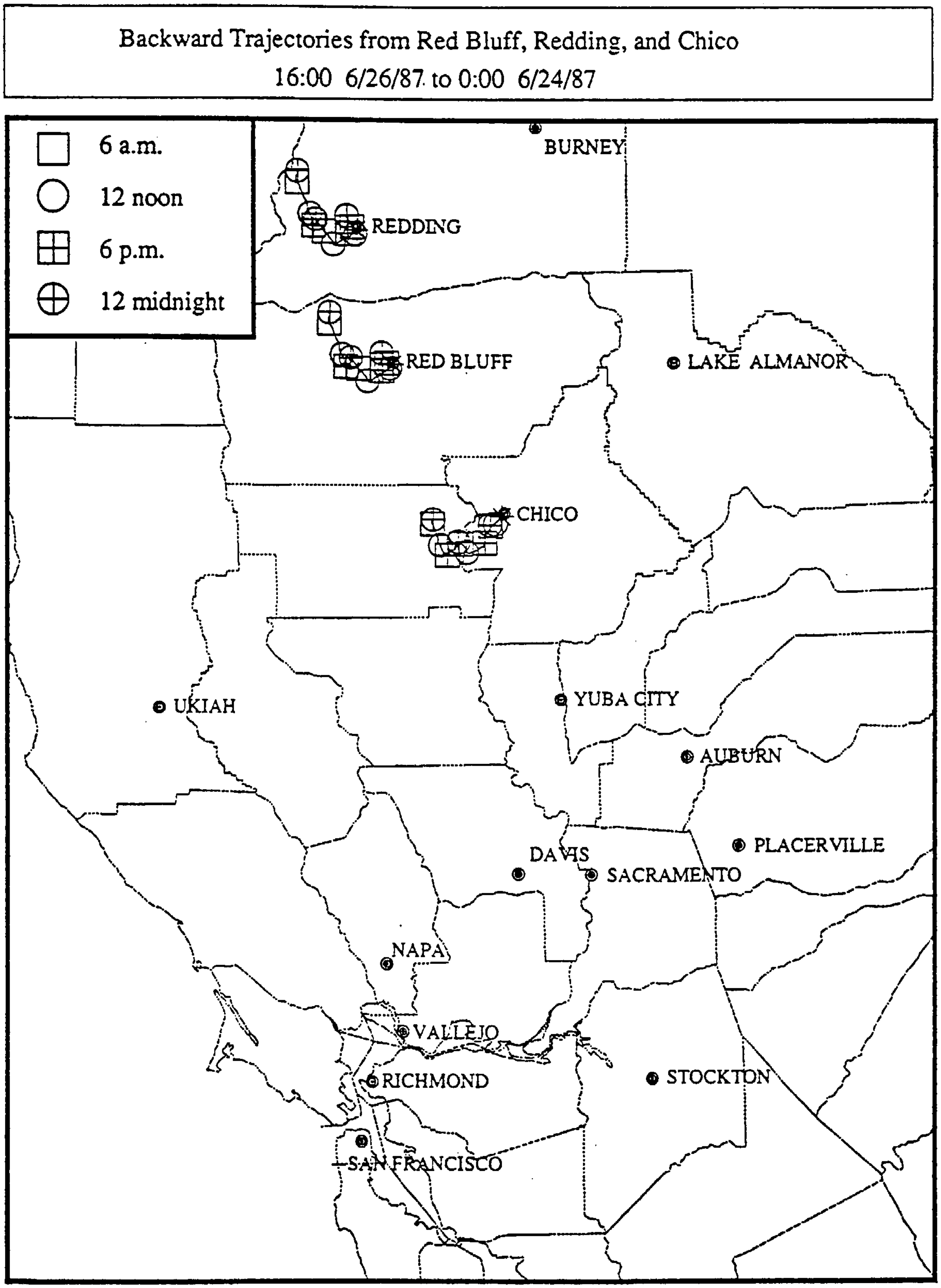


Figure 6-2. Surface back trajectories from Red Bluff, Redding, and Chico on June 26, 1987 beginning at 1600 PST.

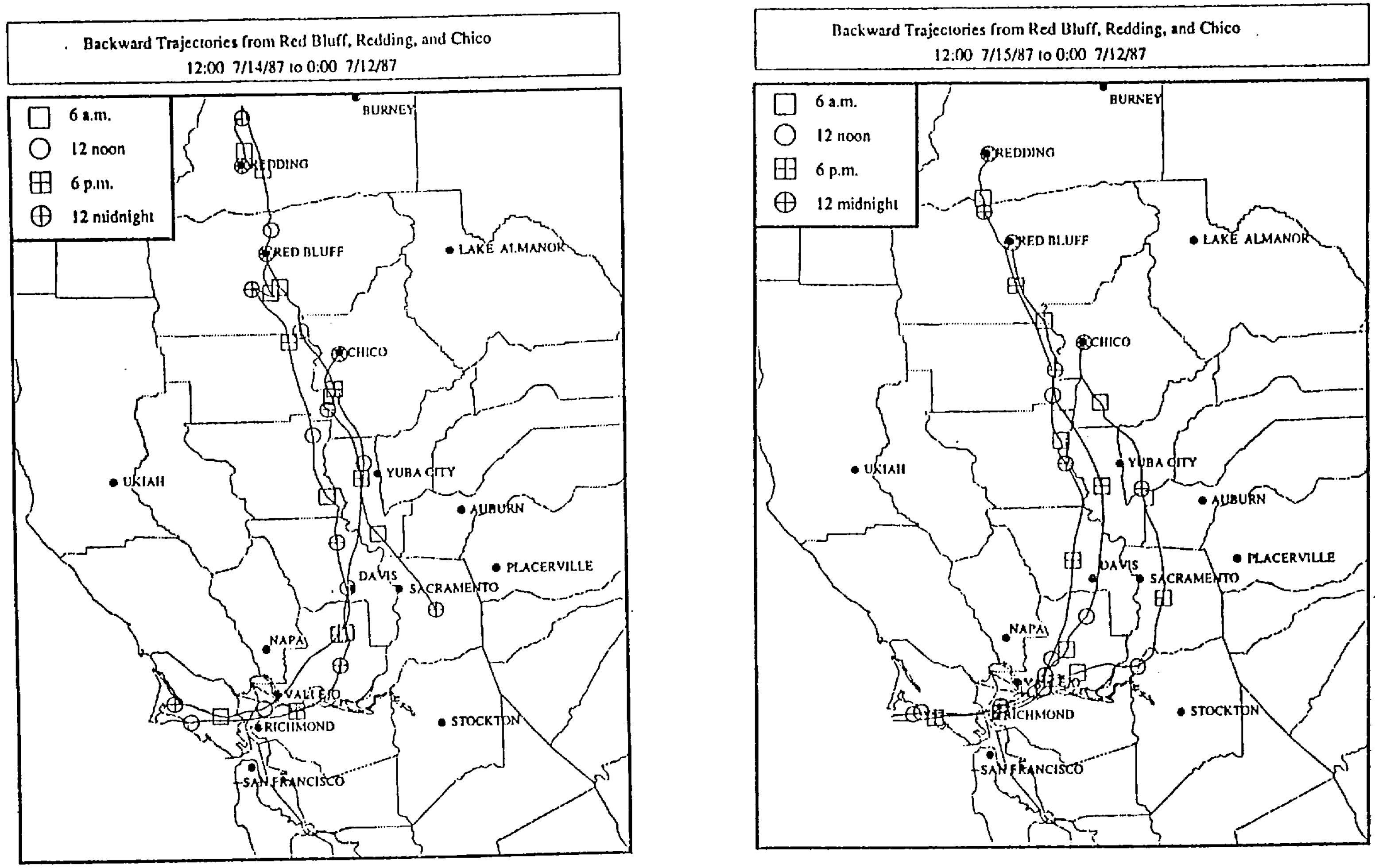


Figure 6-3. Surface back trajectories from Red Bluff, Redding, and Chico on July 14 and 15, 1987 beginning at 1200 PST.

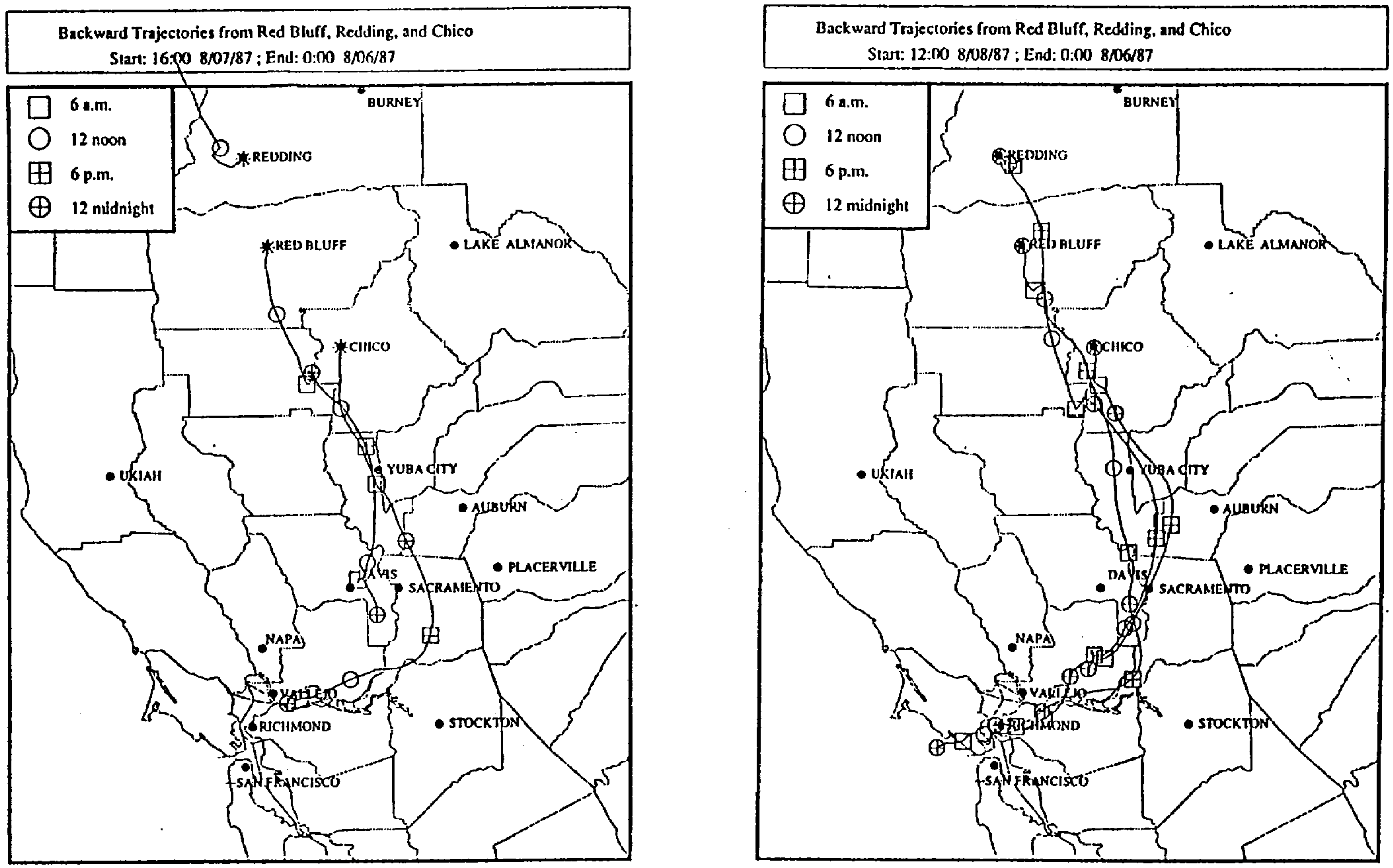


Figure 6-4. Surface back trajectories from Red Bluff, Redding, and Chico on August 7, 1987 beginning at 1600 PST and on August 8, 1987 beginning at 1200 PST.

8 and 9 pphm at Chico. The trajectories show slow transport up the Sacramento Valley, with some trajectories beginning in the SFBAAB. The July 14 Redding trajectory indicates that the air parcel had been in the Redding area since the night before, but had been transported up the valley on the previous day. This illustrates how pollutant carryover might contribute to an ozone exceedance at Redding. The July 15 Redding trajectory shows more direct transport up the valley.

Figure 6-4 shows a different sequence for August 7 and 8, 1987. The only exceedance on August 7 was at Chico (10 pphm maximum at 1700 PST); an 11 pphm maximum was measured at Redding on August 8. The August 7, 1987 1600 PST Red Bluff and Chico trajectories show transport from the Lower Sacramento Valley, while the Redding trajectory shows transport from the north; the trajectories for 1200 and 1400 PST were similar. This shows evidence of a convergence zone between Redding and Red Bluff which separates the northern part of the Upper Sac from emissions sources to the south; this convergence zone is often evident on the ARB wind flow charts. The convergence zone can be further south than Red Bluff on many days, especially in the morning, but this day is an illustration that it can completely block transported pollutants from reaching Redding, at least at the surface.

The August 8, 1987 trajectories from Red Bluff and Chico also shown in Figure 6-4 are similar to the previous day, but the Redding air parcel had arrived from the south. The Redding trajectory indicates that the air parcel had reached an area south of Redding late the previous evening. This is another illustration of how pollutant carryover might contribute to an ozone exceedance at Redding.

6.1.3 Trajectory Results Using Aloft Data

Trajectories were estimated at aloft levels in order to evaluate potential influence of aloft transport on surface ozone concentrations. The 400-meter level was chosen to represent a typical polluted air parcel within the daytime mixed layer; the 800-meter level was chosen to represent an air parcel near the top of or above the daytime mixed layer. Transport winds aloft are typically much faster than those at the surface, especially at night.

Aloft meteorological data are available for several locations in the Sacramento Valley, plus at the Oakland Airport on August 3-5, 1989; July 11-13, 1990; and August 7-10, 1990. During the 1989 period, aloft meteorological data were available every 6 hours at seven sites in the Broader Sac (Prins et al., 1990; and Prins and Prouty, 1990). The northern-most sites were near Kirkville, and at Nicolas and Lincoln. During the July 1990 period, aloft meteorological data were available every 4 hours at four sites in the Broader Sac (Prins and Prouty, 1991a and 1991b), plus every 6 hours at two sites in the Upper Sac (Prins and Prouty, 1991c and 1991d). The northern-most sites were at Maxwell and about 10 km northeast of Yuba City. During August 7-10, 1990, data were available only from the four Broader Sac sites (Prins and Prouty, 1991a and 1991b). We did not prepare aloft trajectories for the August 10-12, 1990 period because aloft meteorological data were only available at two sites after 1800 PDT on August 10.

We prepared 400- and 800-meter wind fields for August 3-5, 1989, August 15-16, 1989, and July 11-13, 1990. Because of fewer sites, we prepared only 400-meter wind fields for August 7-10, 1990. We then estimated forward and backward trajectories for selected locations and times. We prepared a total of 177 forward and backward trajectories. The following discussion illustrates the general characteristics of those trajectories and summarizes the transport results.

Figures 6-5 and 6-6 show back trajectories from Chico on August 5, 1989 at 1600 PST using surface, and 400- and 800-meter winds, respectively. Maximum ozone concentrations were 8 pphm at Redding and 9 pphm at Chico. The surface and 400-meter trajectories show a consistent path from the Broader Sac and the SF Bay Area. However, the speed of the transport is much different; the surface trajectory shows much slower transport than the 400-meter one, more than 2 days from the SF Bay Area versus less than a day. The 800-meter trajectory indicates transport from the area east of Sacramento in 20 to 36 hours. These results are similar to those for the other two 1989 days on which we have aloft data: August 4 and 16.

The aloft trajectories which we have estimated have a major limitation: the lack of data in the northern part of the Sacramento Valley. For the July 11-13, 1990 period, the northern-most upper-air sites were at Maxwell and a location about 10 km northeast of Yuba City. For 1989 and the August 7-10, 1990 period, the northern-most upper-air sites were at Kirkville and Lincoln. Maxwell is about 55 km south of Chico; Kirkville and Lincoln about 90 km; Maxwell is over 130 km from Redding. On a day without a convergence zone in the Upper Sac, the wind data within the mixed layer at Maxwell, for example, may be similar to the actual winds further north toward Red Bluff and Redding. In this case, the uncertainty in air parcel location will be larger than in an area where data exists, but possibly still acceptable for qualitative use. However, on a day with a convergence zone, the wind data within the mixed layer at Maxwell south of the convergence zone is probably very dissimilar to the winds north of the convergence zone, including the area around Redding. In this case the uncertainty would be unacceptable. Thus, we did not use results from any Redding aloft trajectories if there was a convergence zone present.

During 1990, aloft data are available for July 11-13 and August 7-10. The highest ozone concentrations at the Upper Sac sites during the July 11-13 period were at Redding (9 pphm) and at Chico (8 pphm) on July 13. Surface back trajectories for Chico, Red Bluff, and Redding on July 13 had been within about 50 to 75 km of their ending locations for the previous 2 days. Aloft trajectories had been within about 50 to 75 km of their ending locations for the previous day, then went back to the northwest.

During the August 7-10, 1990 period, maximum ozone concentrations were 13 pphm at Redding on the August 7, 12 pphm at Chico on August 8, and 13 pphm at Chico on August 9 (see Figure 6-7). On August 7 notice the almost straight-line rise in ozone concentrations to a sharp peak at 1200 PST, a typical time for a Redding peak. We will use surface and aloft trajectories for Redding and Chico to illustrate the pollutant transport on these days. Several forest fires in the area north and northeast of Chico further complicated a consistent interpretation of this episode.

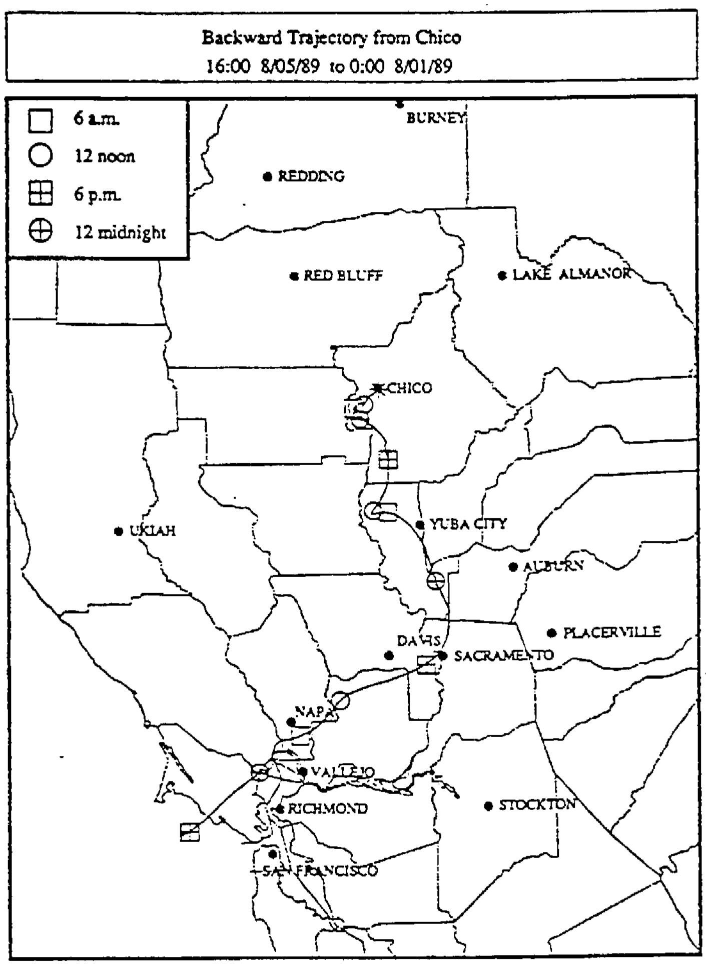


Figure 6-5. Surface back trajectory from Chico on August 5, 1989 beginning at 1600 PST.

(a) (b)

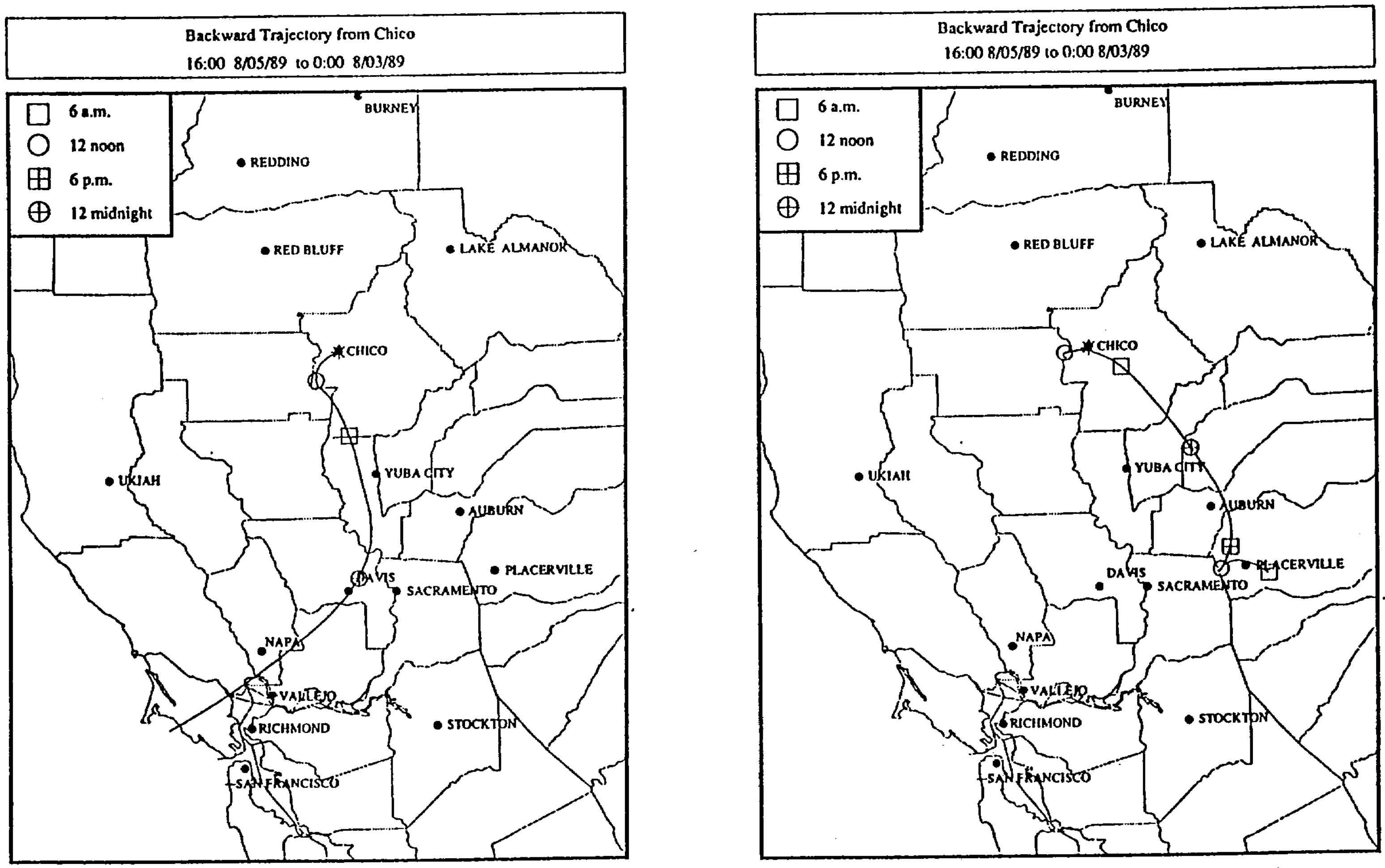


Figure 6-6. Aloft back trajectories from Chico on August 5, 1989 beginning at 1600 PST at (a) 400 meters and (b) 800 meters.

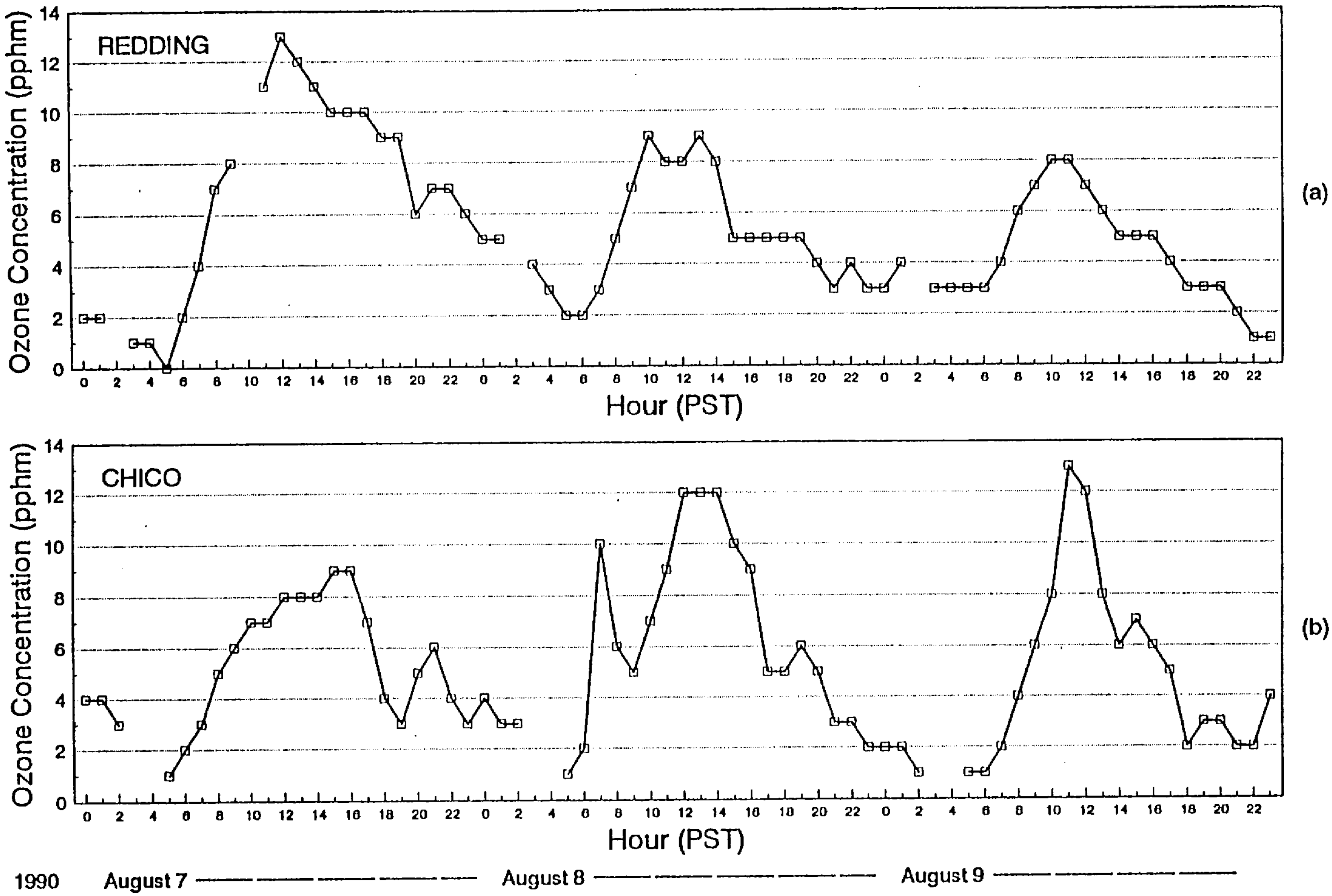


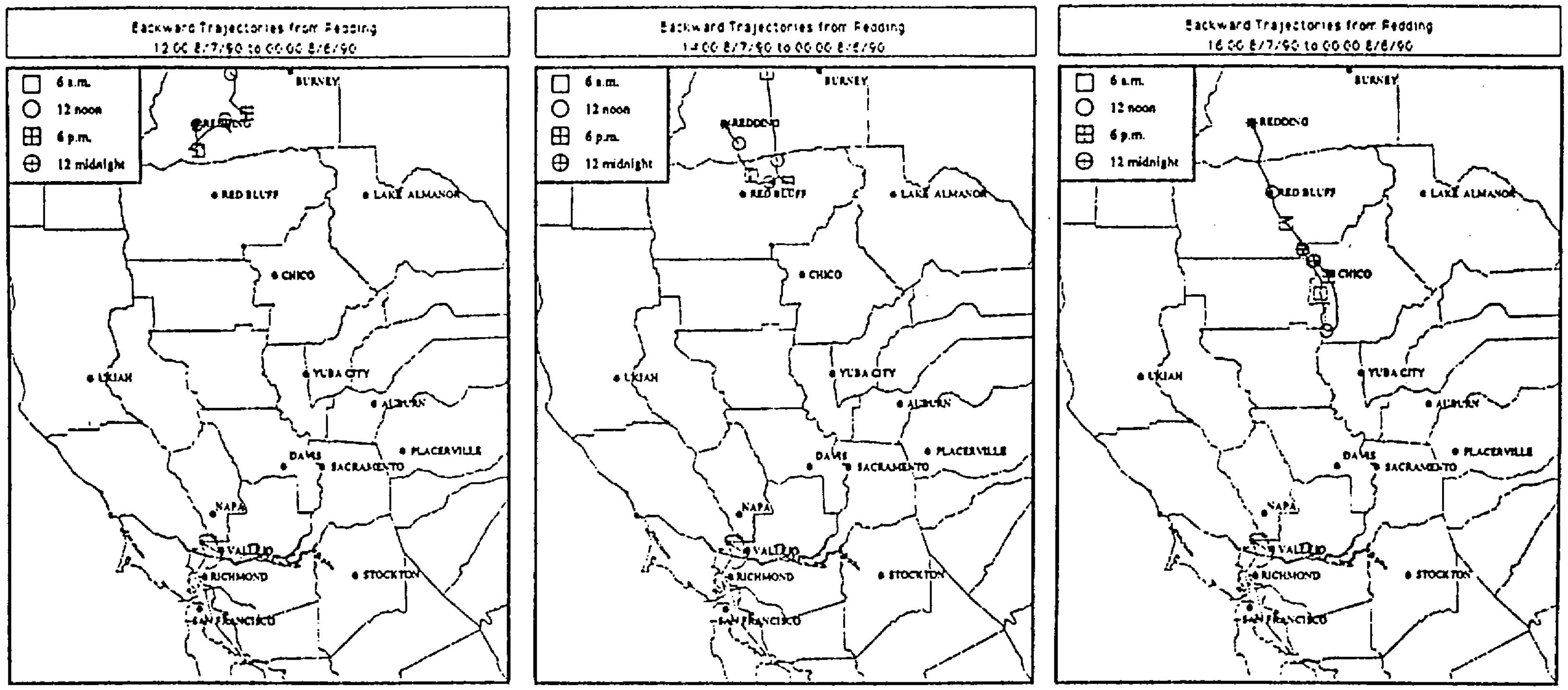
Figure 6-7. Hourly ozone concentrations at (a) Redding and (b) Chico on August 7-9, 1990.

Figure 6-8 shows the Redding surface back trajectories for 1200, 1400, and 1600 PST on August 7, 1990. The 1200 and 1400 PST surface trajectories indicate that the air parcel had arrived in the Redding area from the north late on the previous day. These trajectories probably represent the air parcels arriving during the peak ozone concentration. However, notice that the 1600 PST trajectory indicates arriving air parcels which had been in the Chico area on the previous day.

The aloft trajectory analysis shows fast-moving air parcels arriving from the south. Figure 6-9 shows aloft 400-meter trajectories for this day. Notice how the Redding aloft back trajectory does not follow the Sacramento Valley to the south-southeast, but arrives from the south-southwest across the coast range. The forward trajectory from Howe Park does the opposite: it travels almost due north on August 7 and arrives at about the Redding latitude before midnight. However, this forward trajectory crosses into the high plateau and foothills on the eastern side of the Sacramento Valley. The true trajectory probably lies somewhere in between. These trajectory results are probably an artifact of the data, since the aloft data are from sites at the northern edge of the Broader Sac where the afternoon flow is from the south-southwest. If we had 400-meter wind data from locations further north in the Sacramento Valley, we would probably find that the Redding aloft trajectory had arrived from the Broader Sac.

The diurnal ozone concentrations for Chico on August 8, 1990 were shown in Figure 6-7. There are two ozone peaks, a very short one at 0700 PST and a broad peak at 1200 to 1400 PST. The surface back trajectories for Redding and Chico on this day are shown in Figure 6-10. Notice that there is a convergence zone in the Upper Sac somewhere between Chico and Redding. The Chico trajectory indicates that the 1200 to 1400 PST ozone peak had arrived in the Chico area the previous evening about 1800 PST and had remained in the area. This arrival time is consistent with the ozone peak at about 1500 to 1600 PST on August 7. Figure 6-11 shows the 400-meter back trajectory for Chico. The aloft trajectory indicates a drainage flow out of the foothill area northeast of Chico in the morning. Although these winds should be used with caution because they are generated using data further south, they still show realistic timing and seem to match the conditions on this day. The early-morning ozone peak may be the result of re-circulation of material which left Chico on the previous day.

Flows were different on August 9. Both the Chico surface and 400-meter back trajectories arrived from the north-northwest; the trajectories indicate that the air parcels had been in the Redding area the previous afternoon and evening. However, this air mass could have been part of the air mass that arrived in the Upper Sac on the afternoon of August 7 (see Chico back trajectory in Figure 6-10, for example). If this is the same air mass, then this episode is an example of transport into the Upper Sac on August 7 and then emissions accumulation and continued reaction with little net transport for the next 2 days.



(a) (b) (c)

Figure 6-8. Surface back trajectories from Redding on August 7, 1990 beginning at (a) 1200, (b) 1400, and (c) 1600 PST.

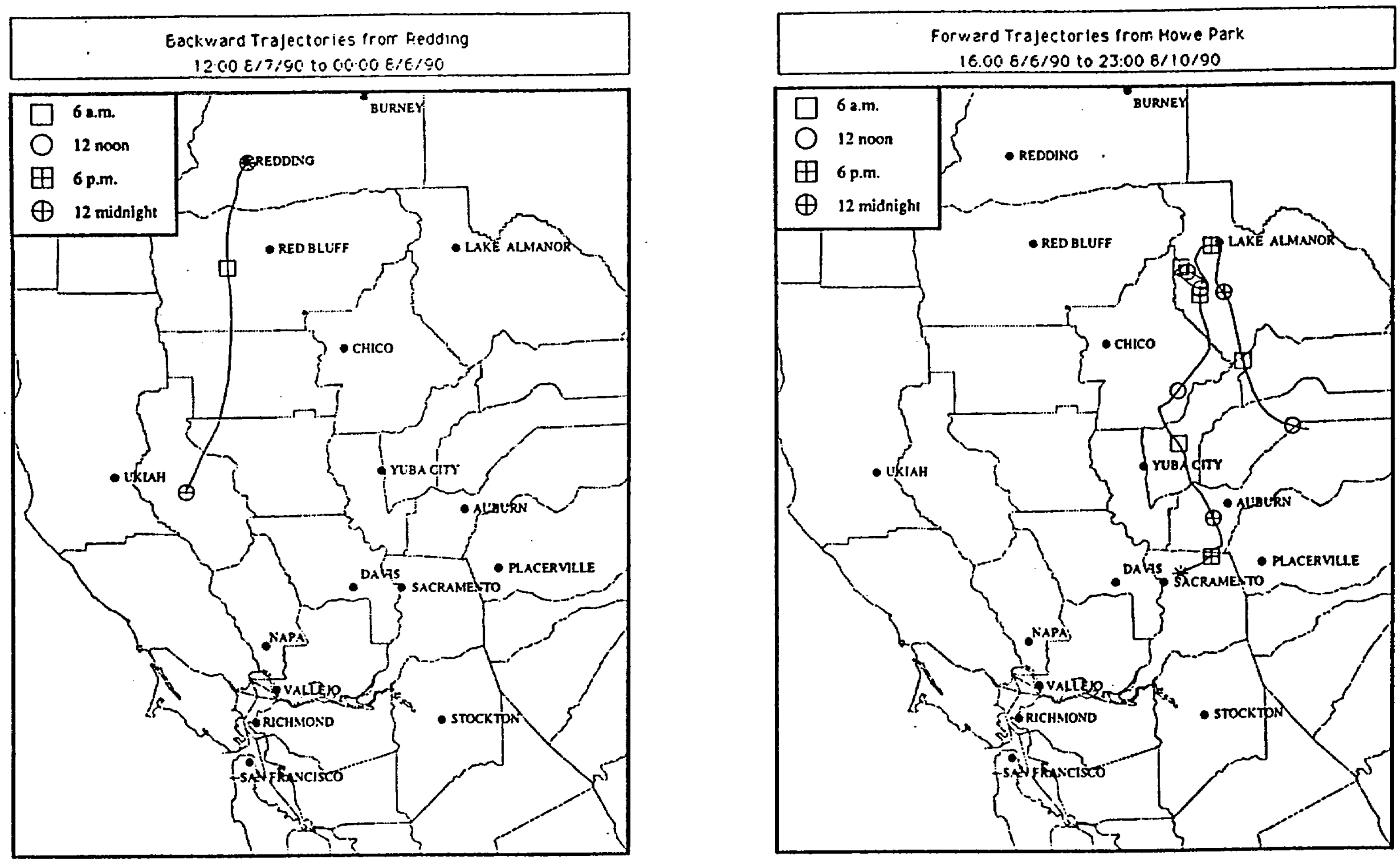


Figure 6-9. Aloft 400 m back trajectory from Redding on August 7, 1990 beginning at 1200 PST, and 400 m forward trajectory from Howe Park on August 6, 1990 beginning at 1600 PST.

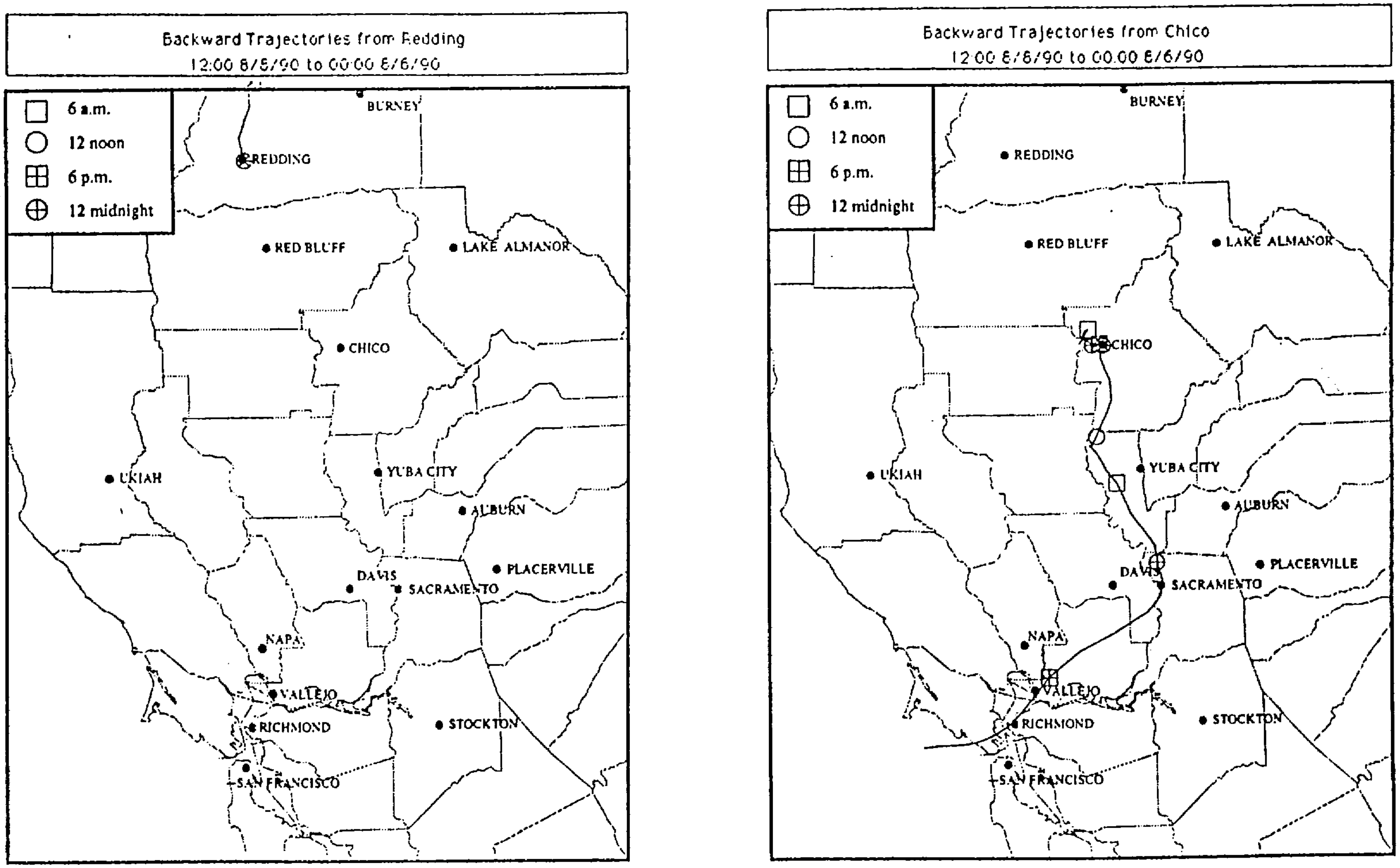


Figure 6-10. Surface back trajectories from Redding and Chico on August 8, 1990 beginning at 1200 PST.

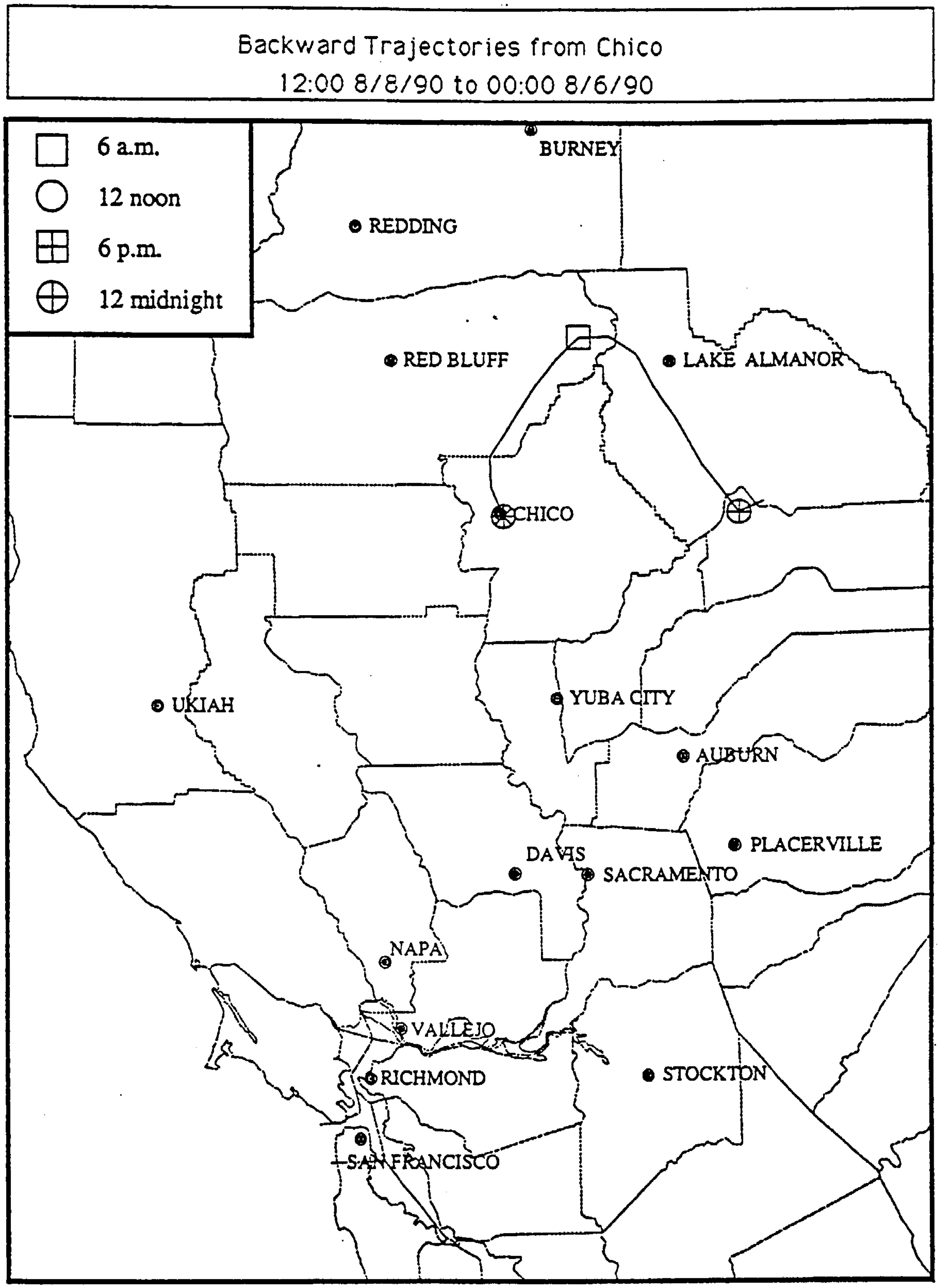


Figure 6-11. Aloft 400 m back trajectories from Chico on August 8, 1990 beginning at 1200 PST.

6.2 PRECURSOR CONTRIBUTION ESTIMATES

This section is divided into three parts. The first two summarize the general methods that were used to generate precursor emissions inventories for California and to estimate the relative precursor contributions to air parcels arriving at receptor sites in the Upper Sac. The third section summarizes the results of our precursor contribution estimates for the Upper Sac and discusses those results. The purpose of these analyses is to quantify the relative contributions of transported and local precursors to ozone violations in the Upper Sac. As ozone precursors, we are concerned with nitrogen oxides (NO_x) and reactive organic gases (ROG).

6.2.1 Summary of Emissions Inventory Methods

A gridded ROG and NO_x emissions inventory was prepared for the domain of interest. Emissions were gridded separately for area sources, biogenic sources, on-road motor vehicles, and point sources. This inventory was prepared from the 1985 National Acid Precipitation Assessment Program (NAPAP) inventory in the following manner:

<u>Point Sources:</u> Emissions were spatially allocated to grid cells based on the location data provided in the NAPAP inventory. Temporal adjustment from annual average emissions to summer weekday emissions was accomplished using the operating information for each point. Missing temporal allocation data were replaced with default parameters (24 hours per day, 7 days per week, 52 weeks per year operation). THC emissions were converted to ROG emissions (reported in CH_4 weight equivalents) using standard EPA volatile organic compounds (VOC) speciation profiles by process.

<u>Area Sources:</u> Emissions were spatially allocated to grid cells using a variety of spatial surrogate indicators; including population, county area, and the following land-use categories: urban, agricultural, rural, range, and water. To temporally adjust emissions from annual average to summer weekday levels, ARB default temporal profiles by source category were used by pairing ARB source categories with NAPAP source categories. THC emissions were converted to ROG emissions using standard EPA VOC speciation profiles by process.

<u>On-Road Motor Vehicles:</u> Emissions from on-road motor vehicles were adjusted from the annual average emissions provided in NAPAP by applying the ratio of MOBILE4 emission factors calculated at typical July temperatures and summer Reid vapor pressure (RVP) to emission factors calculated at the average temperatures and RVPs used to generate the NAPAP inventory. At this point, composite emissions were also disaggregated into exhaust, evaporative, refueling, and running loss components. This was done separately for various climatological regions of California, including the northeast interior basin, the Sacramento Valley, and the central coast. Additional seasonal adjustments based on standard vehicle miles traveled (VMT) and monthly variations from ARB were also applied. Emissions were then spatially allocated according to a combination of population, urban, and rural land-use surrogates. THC emissions were converted to ROG emissions using standard EPA VOC speciation profiles for exhaust and evaporative mobile source emissions by vehicle type. Note that recent analyses (see Fujita et al., 1991, for example) indicate that

motor vehicle emissions might be underestimated. Although this underestimation likely applies to the data we used, it is unlikely to significantly modify the relative contributions we estimated, since any correction would apply to both upwind and downwind regions.

Biogenic Emissions: Summer biogenic emissions of isoprene, a-pinene, and other nonmethane hydrocarbons were obtained at the county level from the Washington State University national biogenic inventory and spatially allocated using land-use surrogates. Temporal allocation of emissions by hour was accomplished using representative diurnal temperature and light intensity curves. Emissions were converted to Carbon Bond 4 species and reaggregated as ROG to provide a compatible format with the anthropogenic inventory components described above. There are no NO_x emissions from this source.

Within the funding available for this study, we were not able to provide any quality assurance or uncertainty analyses of the emissions data used in the gridding process. We used default parameters for all missing data such as temporal allocation factors.

6.2.2 Summary of Precursor Contribution Estimate Method

The next step in our analysis procedure is to estimate the relative emissions contributions of upwind and downwind areas to downwind ozone exceedances. There are a number of methods to estimate these contributions, from simple to more complex. As the method gets more complex, the strength of the transport conclusion increases. Possible methods to estimate the relative emissions contributions include:

- A simple ratio of precursor emissions in the upwind air basin to those in the downwind air basin;
- A simple ratio of precursor emissions in a portion of the upwind air basin (that portion most connected by geography and wind patterns to the downwind area) to those in the downwind area;
- A ratio of upwind to downwind emissions, with emissions accumulated along a typical trajectory path. Separate emissions can be accumulated upwind and downwind of a division between the air basins.
- A ratio of upwind to downwind emissions, using meteorological and photochemical models.

We selected a method which accumulates the emissions along a typical trajectory path. Using this method, the presence of emissions in an arriving air parcel indicates that emissions could have been transported to the receptor. We have estimated the relative amount of precursor emissions from an upwind air basin contained in an arriving air parcel, compared with emissions from other upwind air basins and the receptor air basin. This estimated relative contribution is not an estimate of the amount of ozone formed from upwind precursors during transport along the trajectory; this can only be addressed with photochemical modeling. However, we have assumed that the relative precursor contribution to precursor concentrations in an arriving air parcel is related to the potential to form ozone. In addition, the relative precursor contribution is related to the amount of ozone formed from upwind precursors.

The method that we used involved the following steps:

- Selected the trajectories to use in the analysis. In general we selected back trajectories which arrived at the receptor locations about the time of the peak ozone concentration. Once the trajectories were selected, we performed the emissions accumulation from the source end of the trajectory forward in time to the receptor.

- Prepared the emissions data for processing with the trajectories. The hourly emissions were on a 10-km by 10-km grid. Emissions for each source area were labeled as separate species.

- Moved a 45-km wide box along the trajectory path in 30-minute time steps. A wide box was used to reduce differences in accumulated emissions with small changes in the trajectory path. The 45-km wide box was divided into nine cells each 5-km wide. The box and nine cells are shown at one location along a trajectory in Figure 6-12. Note that although we assumed the 45-km wide box to be 1-km deep and 1-km high, this assumption did not affect the relative emissions contributions.

- Accumulated NO_x and ROG emissions in each of nine cells during each 30-minute time step. The accumulated emissions for a given cell were the hourly emissions for the grid located under the center of the cell, divided by two to match the 30-minute time step. Emissions for each source area were accumulated separately. To allow for emissions from four different source areas, this required accounting for eight species, four species each for NO_x and ROG, in each of the nine cells.

- Accumulated emissions along the trajectory with a first-order loss rate for NO_x and for ROG. The rates we used were:

Species	Day (%/hr)	Night (%/hr)
NO_x	15	5
ROG	3	0

  The rates were selected to represent the typical net loss of precursor by reaction and deposition in an urban photochemical system (see, for example, Calvert and Stockwell, 1983; and Atkinson, 1990). This is obviously a simplified assumption, but one which is more realistic than no net loss. The relative emissions contributions with and without reaction can be thought of as bounding the true contributions.

- At the end of the trajectory, we averaged the accumulated emissions for all nine cells together and reported the relative contributions of the four source areas for NO_x and for ROG.

Figure 6-13a shows the relative concentrations of accumulated ROG from different source regions along an example surface trajectory without reaction. The trajectory for this example was shown in Figure 6-5. As the trajectory passes over the SF Bay Area, ROG from the SF Bay Area sources accumulates and

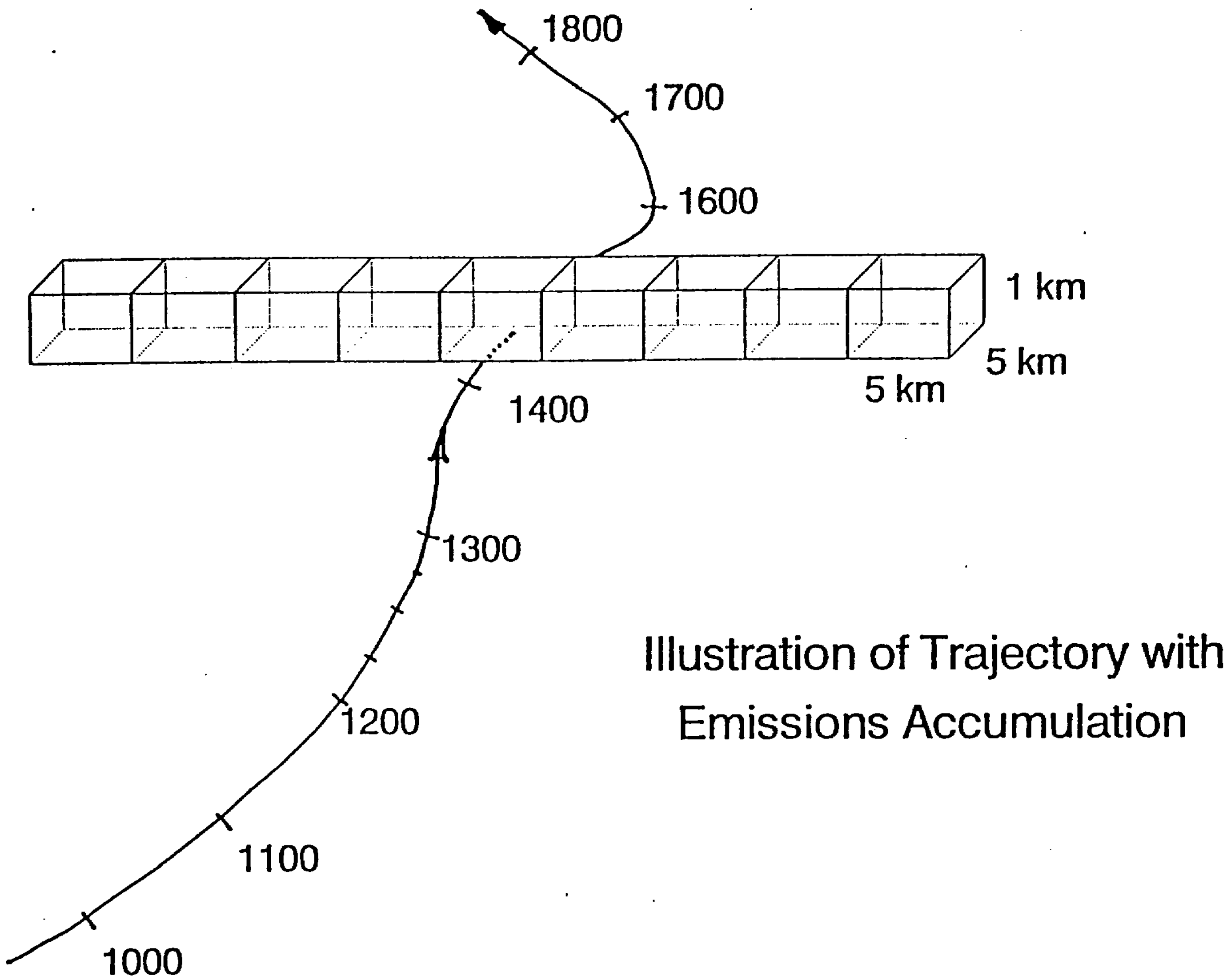


Figure 6-12. Illustration of precursor accumulation geometry along a trajectory path.

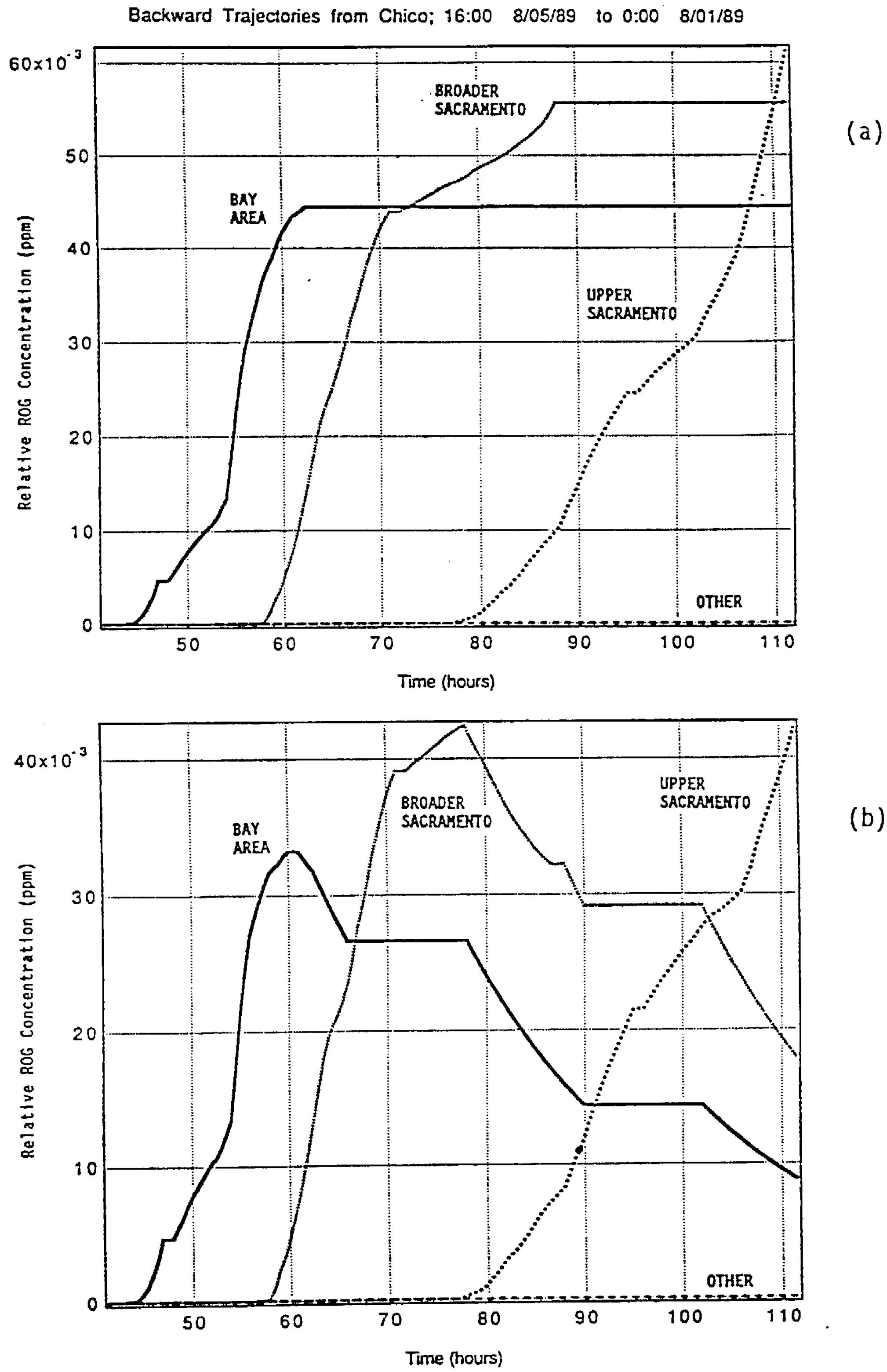


Figure 6-13. Example of ROG accumulation along a surface trajectory path (a) without reaction and (b) with reaction.

eventually remains constant after the trajectory passes into the Broader Sac. Note that there is some accumulation in both source areas while the trajectory is near the boundary between two adjacent areas; this is caused by the wide box. Notice that without reaction, the relative contribution of the three source areas is about equal for this trajectory. This illustrates how the biogenic emissions for the Upper Sac cause a significant contribution to the accumulated ROG for a Chico back trajectory.

When reactions are included, the relative contribution of the SF Bay Area and Sacramento emissions drop significantly (see Figure 6-13b). Because this surface trajectory was quite slow, the accumulated emissions from early along the trajectory path have been reduced significantly by reaction. Notice that there were no losses at night when we have specified the ROG reaction rate to be zero. Now that reaction has been included, the relative contribution of the Upper Sac is much higher than for the case without reaction. A number of examples comparing the relative precursor contributions with and without reaction are shown in Roberts et al. (1992); however, because the case with net loss is more realistic, we have used the reaction rates listed above for all cases illustrated in this report.

Figures 6-14 and 6-15 illustrate the relative influence of using aloft versus surface trajectories for the relative ROG and NO_x precursor contribution estimates. These results are the average of three back trajectories from Chico on August 5, 1990 beginning at 1200, 1400, and 1600 PST. Example surface, 400-meter aloft, and 800-meter aloft trajectories were previously shown in Figures 6-5 and 6-6. The surface and 400-meter aloft trajectories follow a similar path through the Broader Sac and the SF Bay Area. The 800-meter aloft trajectory originated in the Sacramento area and did not pass through the SF Bay Area.

The left-hand set of results in the top and bottom of the Figure 6-14 are the ROG results for the three surface trajectories. The 1600 PST surface trajectory results were discussed above and presented in Figure 6-13. The center and right-hand set of results are for the 400-meter and 800-meter aloft trajectories.

Because the aloft trajectories travel much faster than the surface trajectories, the losses of ROG are much less than with surface trajectories. The relative ROG contributions from the SF Bay Area is increased for the aloft case over the SF Bay Area ROG contributions for the surface trajectory case. However, the dominant conclusion from Figure 6-14 is that under these transport conditions, the local area is contributing a majority of the accumulated ROG, independent of the trajectory height. This is partially caused by the biogenics emitted in the Upper Sac.

Figure 6-15 summarizes the NO_x precursor contributions for surface and aloft back trajectories from Chico on August 5, 1990. This figure is similar to Figure 6-14, except that it is for nitrogen oxides (NO_x). For NO_x, the relative effects when using aloft instead of surface trajectories and when using no reaction instead of reaction are similar to the effects on ROG contributions. However, some of the magnitudes are modified slightly because without biogenics, there are much lower emissions in the Upper Sac. For the

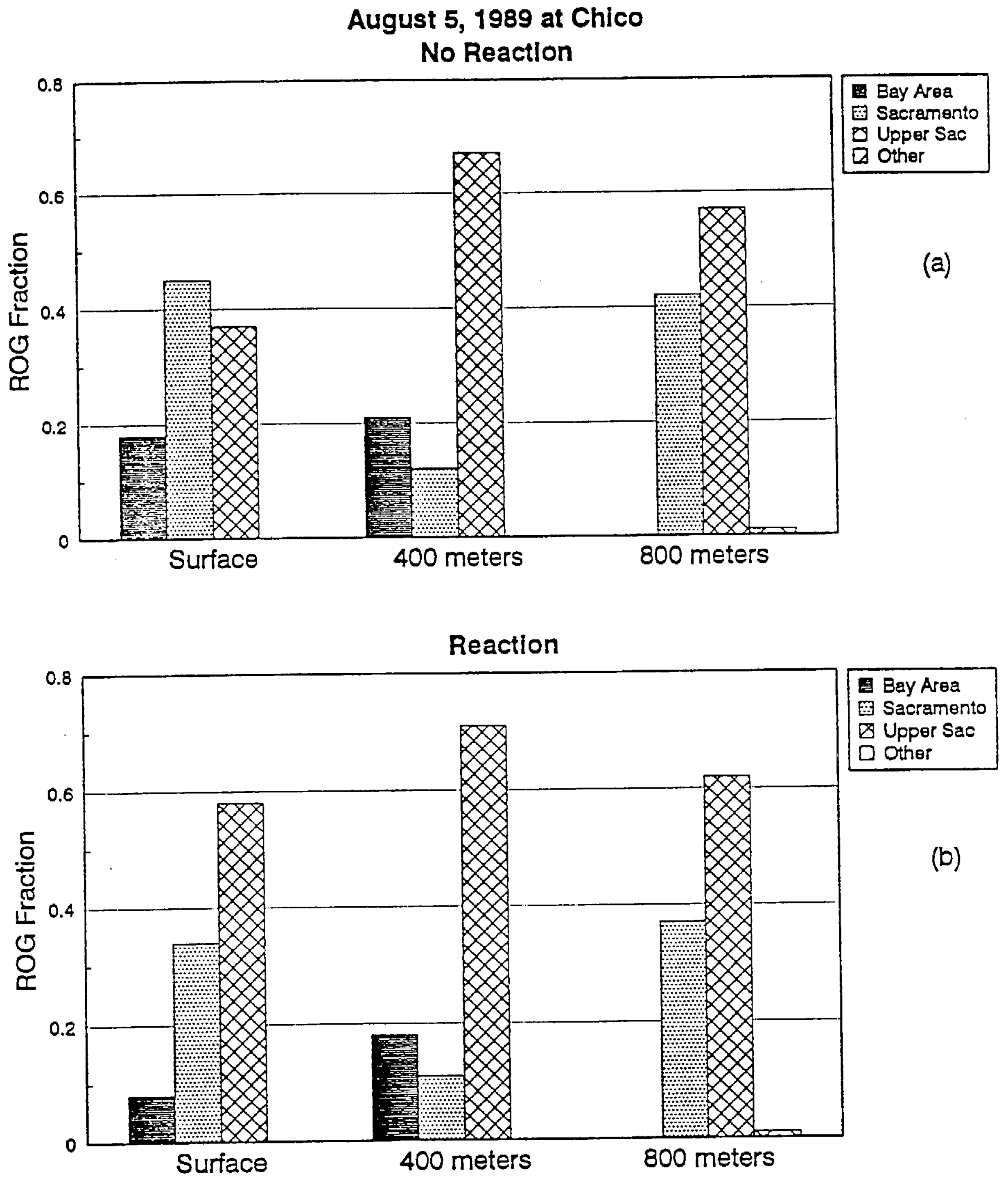


Figure 6-14. ROG emissions contribution estimates (a) without reaction and (b) with reaction for surface, 400 meter, and 800 meter back trajectories from Chico on August 5, 1989 (average of three trajectories at 1200, 1400, and 1600 PST).

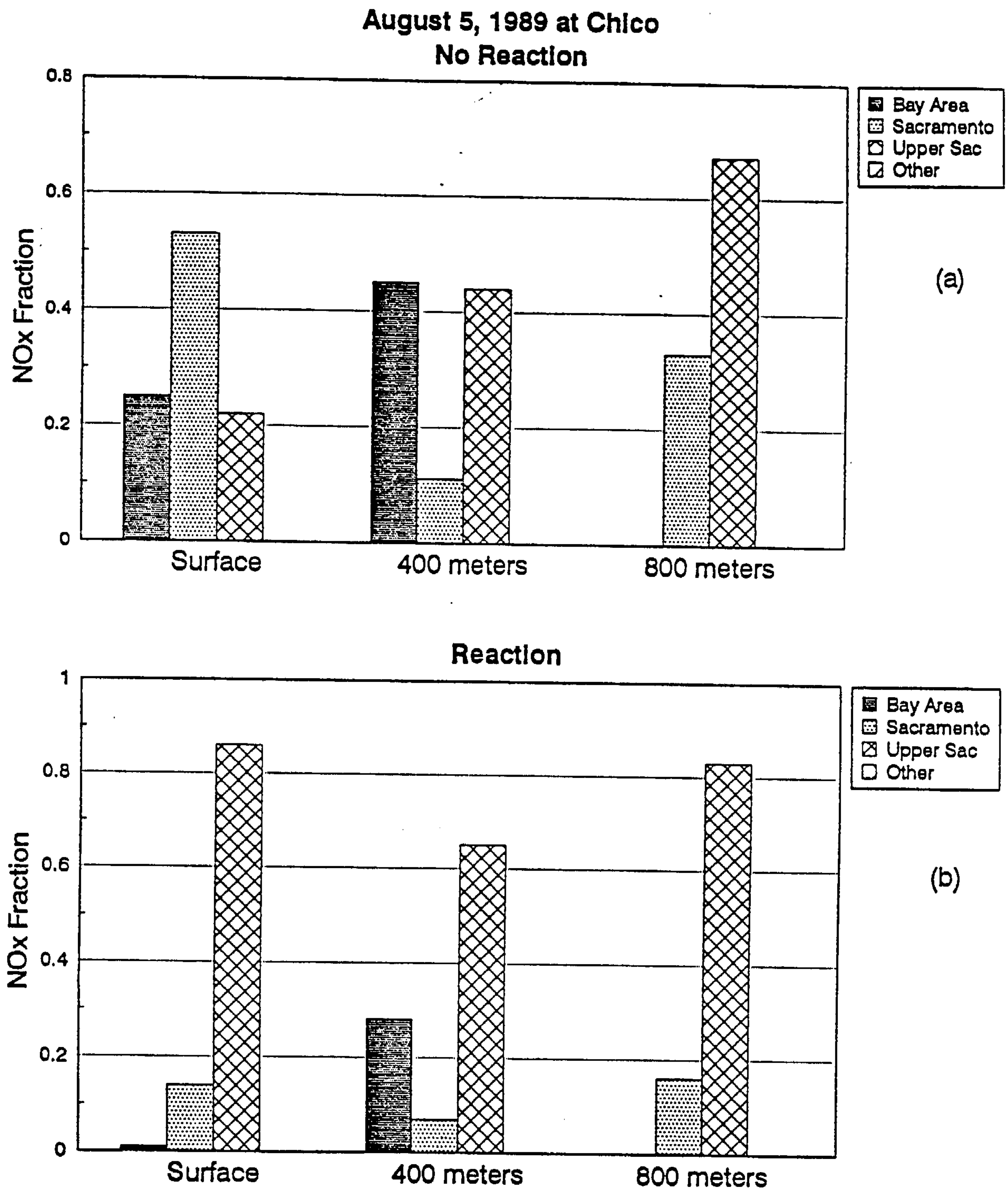


Figure 6-15. NO_x emissions contribution estimates (a) without reaction and (b) with reaction for surface, 400 meter, and 800 meter back trajectories from Chico on August 5, 1989 (average of three trajectories at 1200, 1400, and 1600 PST).

cases with reaction, the Upper Sac contributes a majority of the NO_x to air parcels arriving at Chico on August 5, 1990.

The above discussion used one day as an example to illustrate the methods that we used to estimate precursor contributions and the effects of various assumptions. However, the relative contributions might be different on other days. Figure 6-16 shows the relative precursor contributions for an average of 21 surface back trajectories from Chico on 7 days with high ozone concentrations at Chico. On these 7 transport days during 1989, the maximum ozone concentration at Chico was 10 pphm on 3 days, 9 pphm on 2 days, and 8 pphm on 2 days. On some of the days used for this figure, the surface back trajectories did not extend all the way back to the SF Bay Area, but only as far as the Broader Sac.

When reactions are included for these 7 days in 1989, Figure 6-16 shows that the Upper Sac contributed about one-half of the ROG and one-half of the NO_x, the Broader Sac contributed about one-third of each precursor, and the SF Bay Area contributed about 15 percent of each precursor.

6.2.3 Precursor Contribution Estimates

This section presents precursor contribution estimates at the Upper Sac receptor sites for ozone exceedance days at Redding, Red Bluff, Chico, and Arbuckle. Summaries are presented for precursor estimates for 18 ozone exceedance days at Redding during 1987 and for 10 ozone exceedance days at Chico during 1987 and 1988. Estimates for high ozone days at Chico during 1989 were presented in Section 6.2.2. All of these estimates were obtained using surface trajectories; estimates using aloft trajectories were also presented in Section 6.2.2.

During 1987, ozone concentrations exceeding the state standard were measured on 20 days at Redding and 15 days at Anderson, just south of Redding. On a few of these days, exceedances occurred at both Redding and Anderson. As a result, ozone exceedances occurred at either Redding or Anderson, or both on 25 separate days. Included were 2 days with 13 pphm maxima, 2 days with 12 pphm maxima, and 3 days with 11 pphm maxima. We performed back trajectories beginning at Redding, Red Bluff, and Chico on 18 of these days, including all of the days with maxima above 10 pphm. These 18 days are listed in Table 6-1, along with the maximum ozone concentration at either Redding or Anderson and at Chico. Note that only 2 of these days are also exceedance days at Chico. However, 3 Chico exceedance days occurred a day before a Redding exceedance.

For the 18 exceedance days in 1987 at either Redding or Anderson, we used the surface trajectory results to classify that exceedance as either local (trajectory stayed within about 75 km) or transport (trajectory arrived from beyond about 75 km). Note that this approach does not account for aloft transport. The summary results are shown in Table 6-2. The Redding exceedances are almost exclusively local with only one 3-day episode of transport (July 13-15), whereas at Red Bluff and Chico the same days are about evenly split between local and transport. This result supports the hypothesis that Redding is often separated from the rest of the Sacramento Valley by the convergence zone which forms during the summer between Redding and

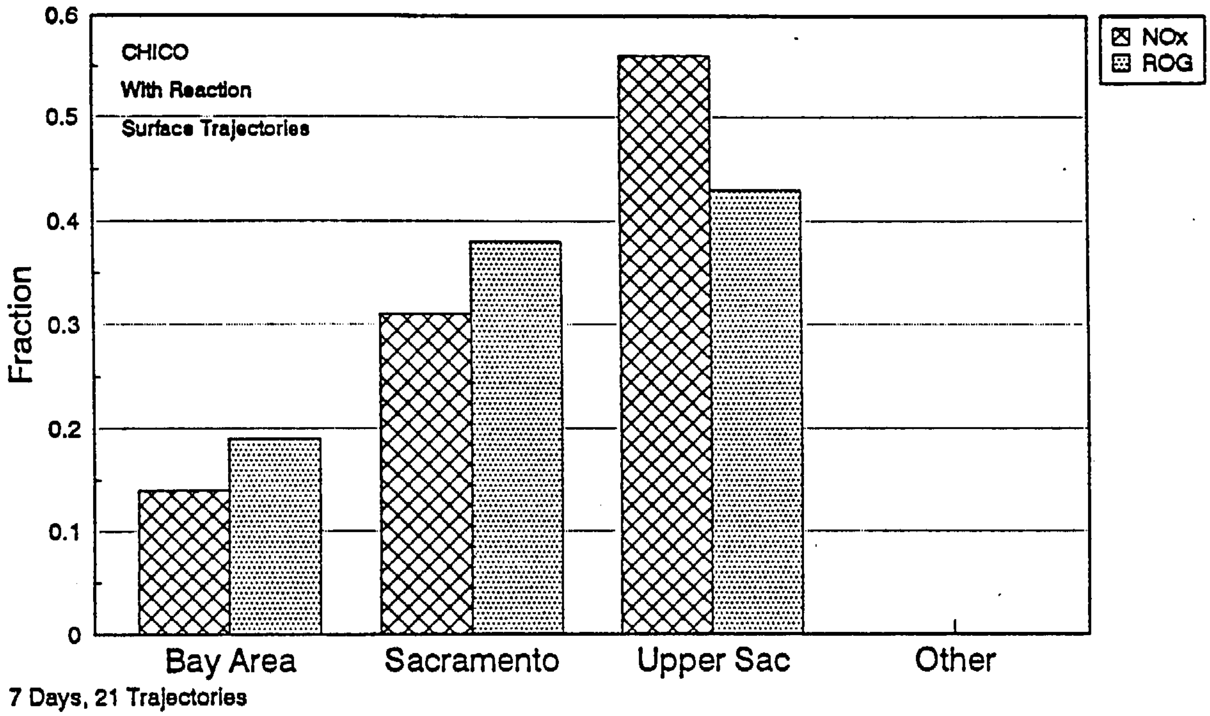


Figure 6-16. Average precursor contribution estimates with reaction for 21 surface back trajectories from Chico on seven days during 1989.

Table 6-1. Redding or Anderson exceedance days during 1987 selected for trajectory analysis and maximum ozone concentrations.[a]

1987 Date	O_3 Max (pphm) at Redding or Anderson	O_3 Max (pphm) at Chico	Transport Days		
			Redding	Red Bluff	Chico
June 3	10	11	-	-	-
June 26	13	10	-	-	-
June 27	10	9	-	-	-
July 13	10	8	✓	✓	✓
July 14	11	9	✓	✓	✓
July 15	10	8	✓	✓	✓
August 4	11	9	-	-	✓
August 8	11	9	-	✓	✓
August 9	10	7	-	✓	✓
August 31	10	9	-	✓	✓
September 1	13	8	-	✓	✓
September 2	10	8	-	✓	✓
September 3	10	8	-	✓	✓
September 9	12	9	-	-	-
September 19	10	9	-	-	-
September 23	12	8	-	✓	✓
October 2	10	9	-	-	-
October 3	10	8	-	-	-

[a] Based on surface trajectories only.

Table 6-2. Classification of 1987 Redding or Anderson exceedance days as transport or local at Redding, Red Bluff, and Chico.

Monitoring Location	No. of Transport Days	No. of Local Days
Redding	3	15
Red Bluff	10	8
Chico	11	7

Sutter Buttes. The convergence zone provides a barrier to transport on many days, at least at the surface.

These classifications were based on surface trajectories only; thus, the air parcels moved slowly and the local area always contributed some precursors. On all transport days both the Upper Sac and the upwind air basins contributed; thus there were no overwhelming transport classifications. Even though the ARB (1990a) did not quantify the definition of overwhelming contribution, we assumed that overwhelming contribution occurred when 80 to 90 percent contribution was from the upwind basin.

Figures 6-17, 6-18, and 6-19 present average precursor contribution estimates at the Upper Sac monitoring sites on 18 exceedance days at either Redding or Anderson during 1987. The average estimates are presented for local (a) and transport (b) trajectories at Redding, Red Bluff, and Chico. The 18 days were listed in Table 6-1 and classified as either local or transport for each site in Table 6-2.

For local trajectories arriving at all three sites, the precursor contributions were all from the Upper Sac. For transport trajectories at Redding, the northern-most monitoring site, the precursor contribution estimates were over 80 percent from the Upper Sac. However, at monitoring sites further south, the contributions for transport trajectories from upwind air basins increased. For trajectories arriving at Red Bluff on these exceedance days, the Upper Sac contributed about 60 percent of the NO_x and ROG precursors, with the SF Bay Area and the Broader Sac contributing 15 to 20 percent. For trajectories arriving at Chico, the Upper Sac and the Broader Sacramento area contributed 30 to 40 percent each, with the SF Bay Area contributing 15 to 25 percent.

Immediately preceding 3 of the 1987 Redding exceedance days classified as local at Redding (July 8 and 9 and September 23), there was an exceedance at Chico. For these 3 days, there might have been the additional possibility of transport aloft to Redding on the subsequent day. This is a weakness with this method when only surface trajectories are used.

During 1987 and 1988 there were 13 state ozone exceedances at the Chico monitoring site; 5 in 1987 and 8 in 1988. All maximum concentrations were 10 pphm. We performed trajectory and precursor contribution estimates for 10 of these 13 exceedances. Of those 10, 4 were local and 6 were significant transport. The average contributions for the 6 transport days (18 trajectories) are shown in Figure 6-20. Note that the SF Bay Area contributes some precursors, but most of the precursors are from the Upper Sac and the Broader Sac.

The ARB (1990a) identified one case of overwhelming transport to the Upper Sac - transport to Arbuckle and Willows on October 7, 1987. Figure 6-21 shows backward surface trajectories for Arbuckle and Willows at 1400 PST on October 7, 1987; trajectories at 1100, 1300, and 1500 PST were similar. Note that the northerly flow on the previous day kept the Willows back trajectory within the Sacramento Valley, while the Arbuckle back trajectory had arrived from the SF Bay Area. This difference produced a marked difference in precursor contribution estimates (see Figure 6-22); the SF Bay Area

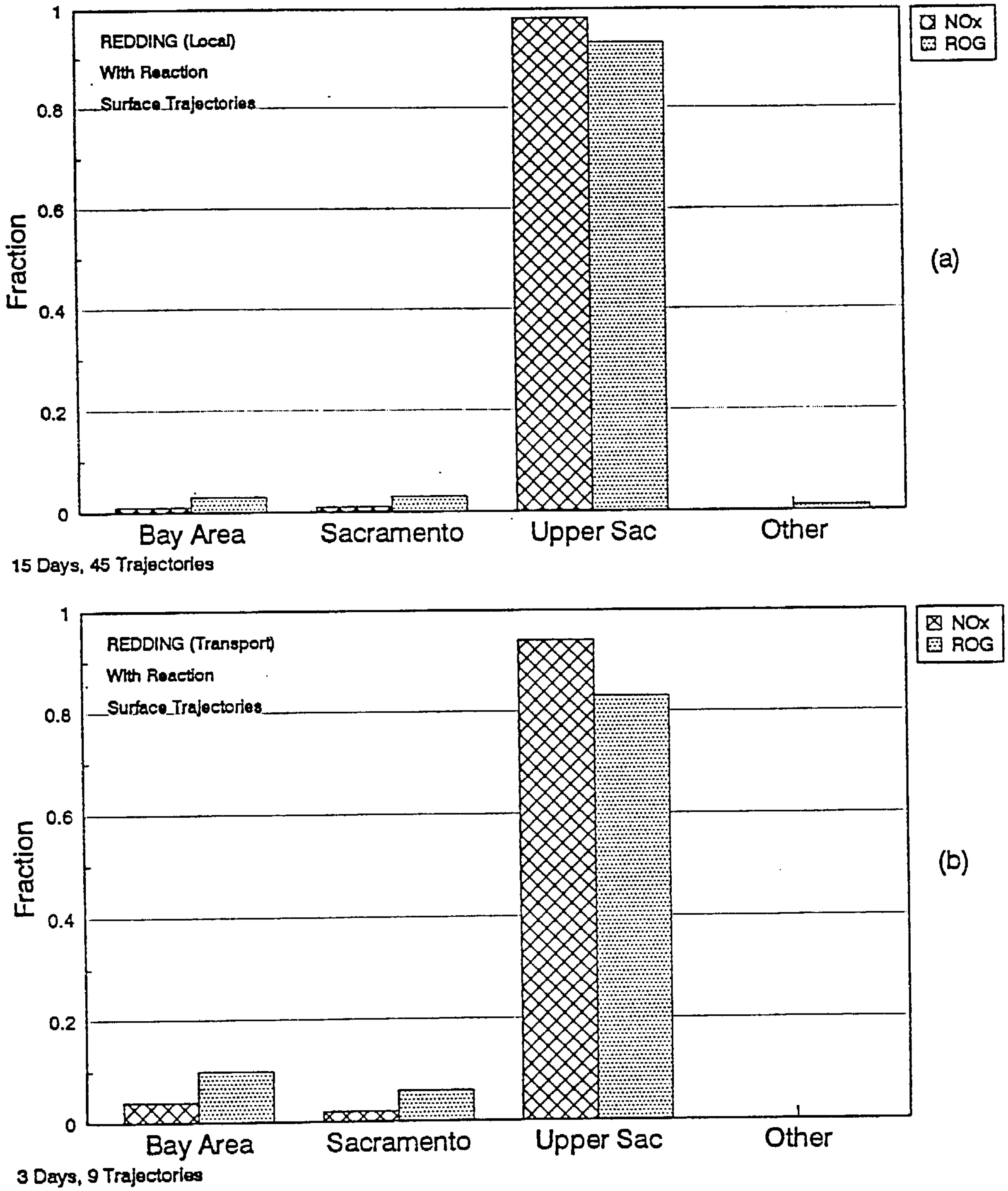
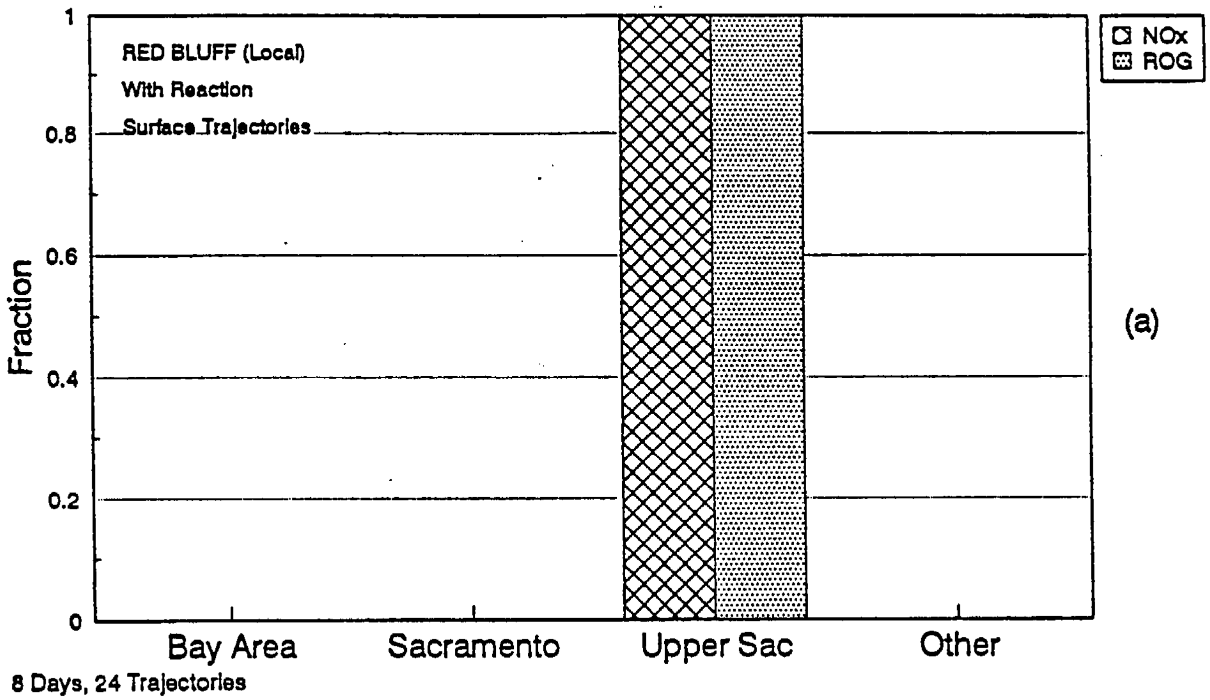


Figure 6-17. Average precursor contribution estimates for (a) local and (b) transport exceedance days at Redding using surface trajectories (18 exceedance days at either Redding or Anderson during 1987).



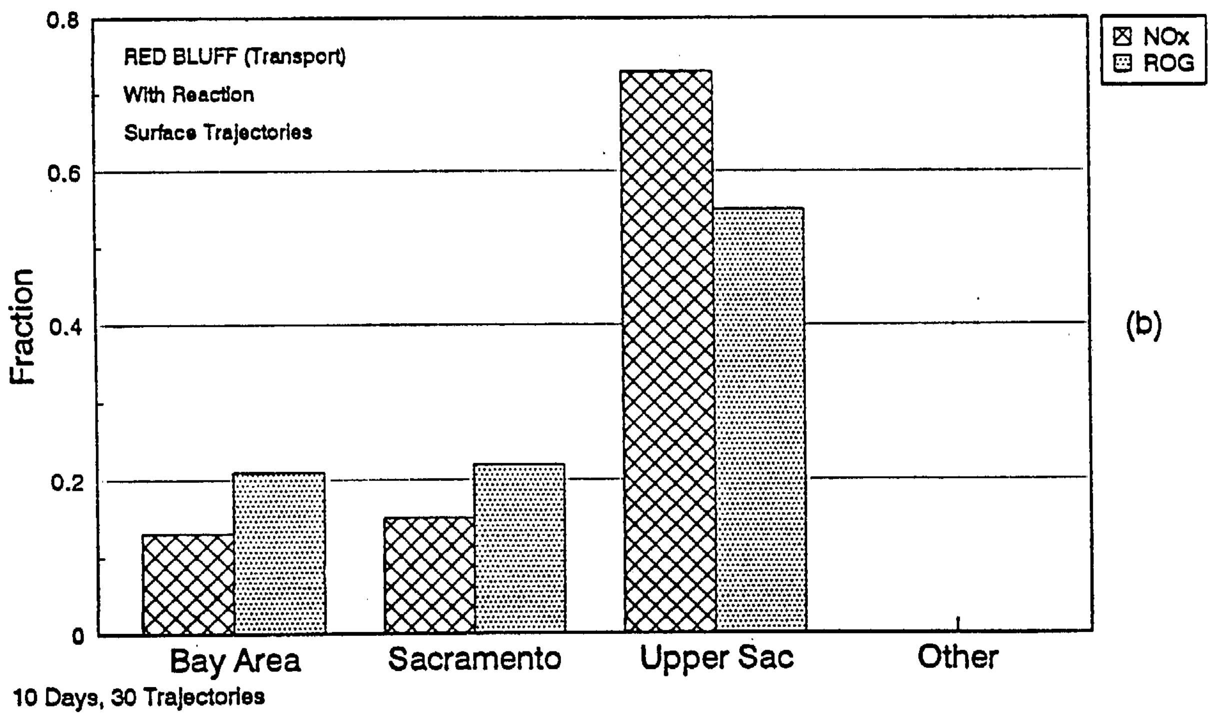


Figure 6-18. Average precursor contribution estimates for (a) local and (b) transport days at Red Bluff using surface trajectories (18 exceedance days at either Redding or Anderson during 1987).

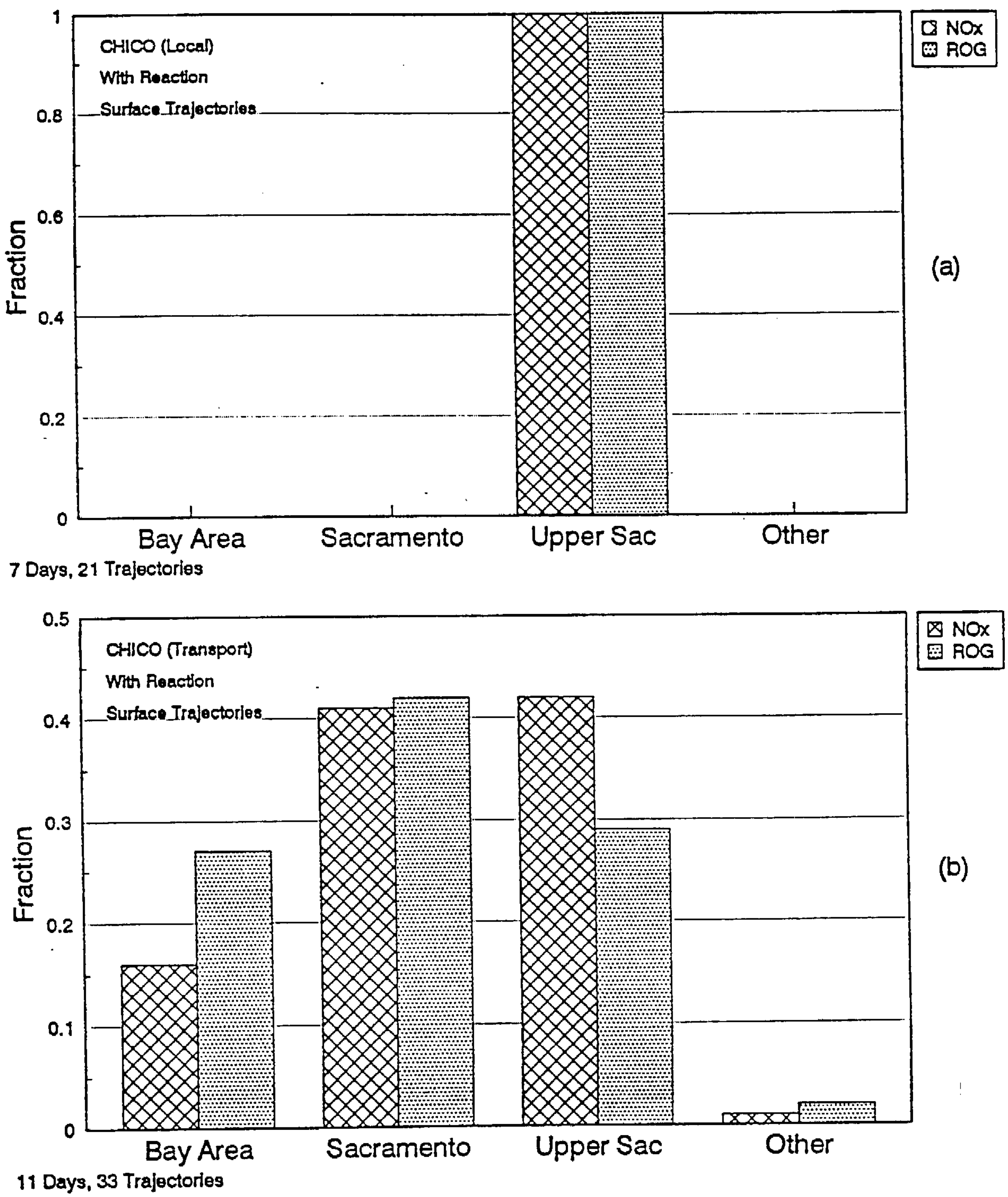


Figure 6-19. Average precursor contribution estimates for (a) local and (b) transport days at Chico using surface trajectories (18 exceedance days at either Redding or Anderson during 1987).

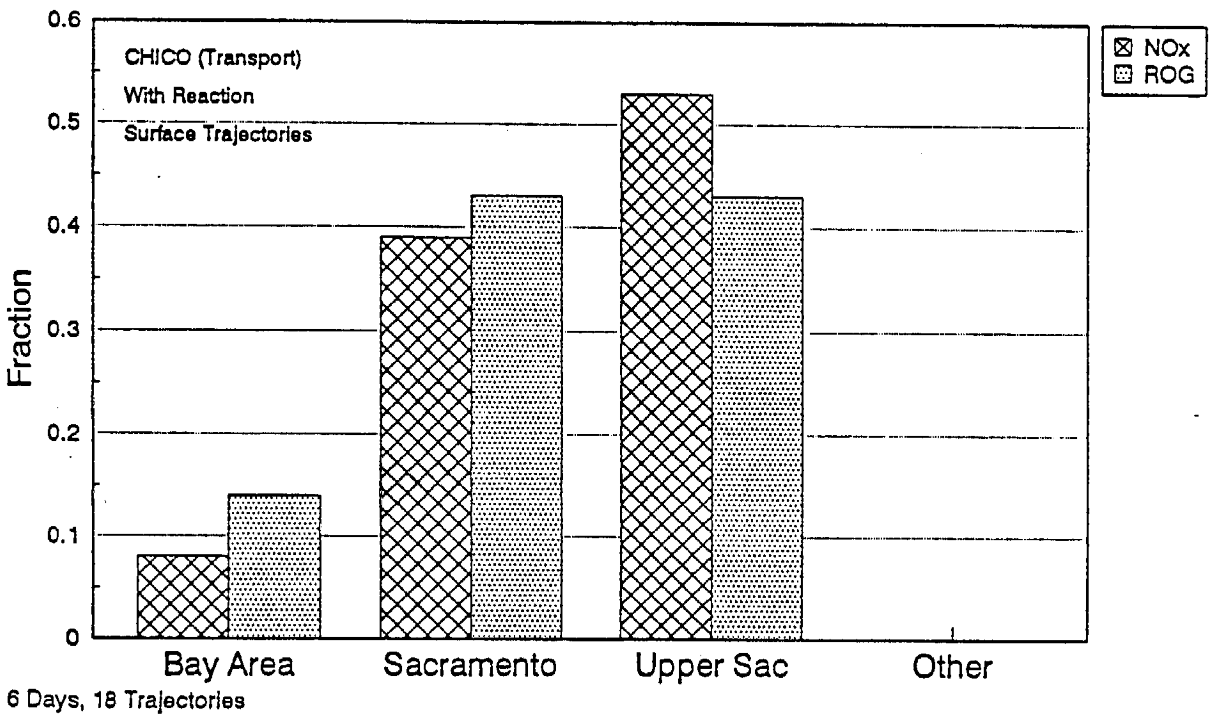


Figure 6-20. Average precursor contribution estimates for transport exceedance days at Chico using surface trajectories (six exceedance days at Chico during 1987 and 1988).

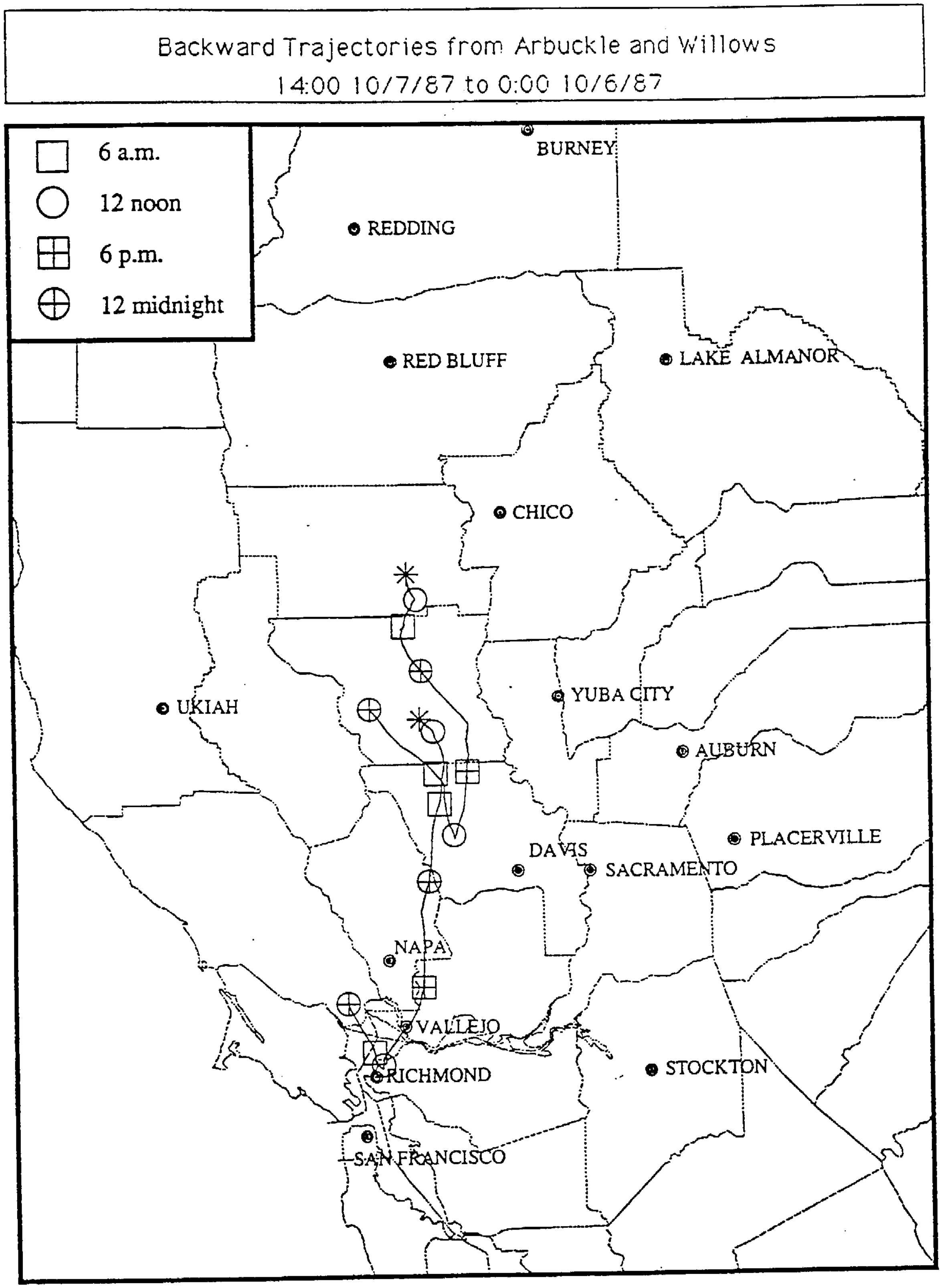
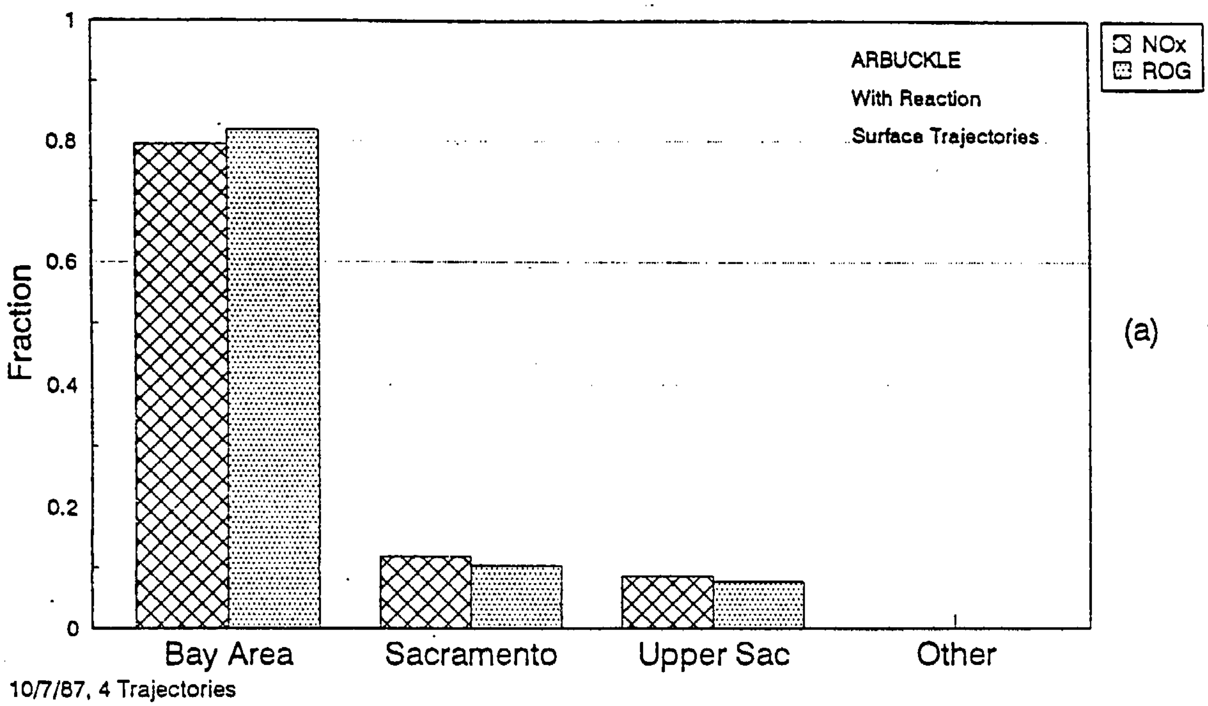


Figure 6-21. Surface back trajectories from Arbuckle and Willows on October 7, 1987 beginning at 1400 PST.



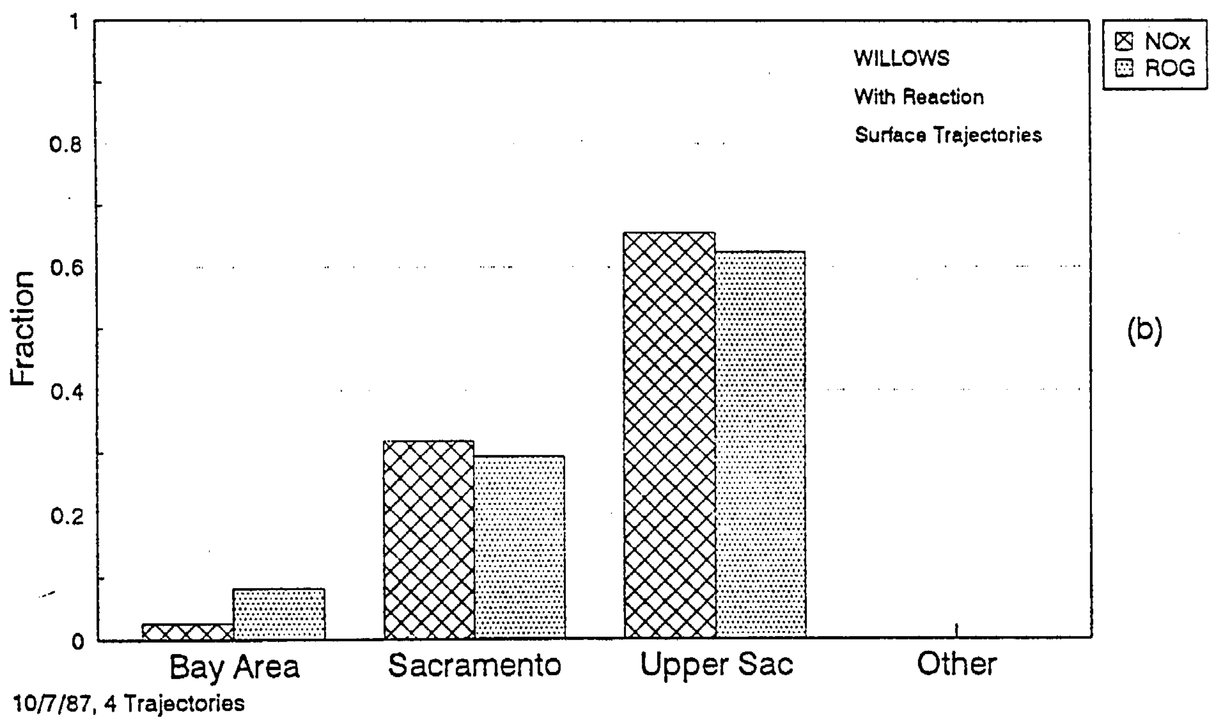


Figure 6-22. Average precursor contribution estimates for October 7, 1987 at (a) Arbuckle and (b) Willows using surface trajectories.

contributed about 80 percent of the ROG and NO_x and the Upper Sac less than 10 percent at Arbuckle, while the Upper Sac contributed 65 to 70 percent at Willows.

6.3 ANALYSIS RESULTS USING TRAJECTORY METHODS

The following is a summary of the results of our analyses using trajectory methods. The general results on transport-path analyses and precursor contribution estimates include comments on how well the data analysis methods performed and the major assumptions and limitations of the methods, as well as comments on the relative contributions of the various areas.

Transport-path Analysis Results:

- Generating large numbers of air parcel trajectories was a good method to identify the consensus transport paths for each receptor.

- Air parcel trajectories generated from surface wind measurements were consistent with expected transport paths based on results from past field, analysis, and modeling studies.

- Wind measurements are required to properly represent transport in the areas where convergence zones occur, such as in the Upper Sac south of Redding. These measurements are required at sites on both sides of the convergence zone, both near the convergence zone and upwind 10 to 30 km.

- Aloft transport to Redding seemed to occur on a number of days, even though a convergence zone was often present at the surface between Redding and the Broader Sac. For example, on August 7, 1990, aloft trajectories indicate transport from the south, but surface trajectories show transport from the northwest most of the day.

- Transport paths using upper-air wind measurements were often consistent with those generated from surface winds, but they were also sometimes different, especially at the 800-meter level.

- When transport paths using upper-air winds were consistent with those using surface winds, the transport aloft was much faster than the transport at the surface. Fast transport aloft increased the precursor contribution of the upwind area, relative to the downwind area. However, this increase was small if same-day transport or transport over short distances was involved. The largest differences between precursor contribution estimates using surface data and those using aloft data occurred when there was overnight transport.

- For most receptor sites, we identified one major transport path. However, for Redding, and possibly Red Bluff on some days, transported pollutants could arrive via either the surface or aloft.

Precursor Contribution Estimate Results:

- The precursor contributions of upwind and downwind areas were estimated for two ozone precursors: reactive organic gases (ROG) and nitrogen oxides (NO_x). The relative contribution estimates of the upwind and downwind areas using ROG were very close to those using NO_x.

- Precursor contribution estimates were made for cases with and without the loss of precursors via reaction and deposition. Including losses via reaction and deposition increased the precursor contributions from the local area and decreased the contributions from the upwind area. Using daytime and nighttime first-order reaction rates for both ROG and NO_x was simple to do and was more realistic than not using any reaction rates. Thus, results are reported for cases with reaction included.

- When pollutant transport to a receptor site occurred, at least 10 to 20 percent of the precursor contributions usually came from the local air basin.

- However, an exception occurred when there was transport from the upwind air basins to Arbuckle, a monitoring site just across the boundary into the Upper Sac, on October 7, 1987. This resulted in about 90 percent precursor contribution from the upwind air basins; we defined this as overwhelming transport to Arbuckle.

- For Chico, Red Bluff, and Redding, we identified ozone violation days with both local and transport contributions. However, none of these transport days were overwhelming.

- We used an emissions inventory which included an estimate of biogenic emissions; these biogenic emissions estimates are significant in the Upper Sac. Therefore, for the receptor sites well away from the upwind boundary (i.e., Chico, Red Bluff, and Redding), we estimated that there was an ROG precursor contribution of at least 30 to 40 percent from the local air basin.

- Precursor contribution estimates using aloft trajectories resulted in larger contributions from the upwind area than did estimates using surface trajectories. This is because the aloft trajectories result in faster transport with less time for precursors to be lost via reaction and deposition.

- The combined trajectory/precursor contribution estimate method worked best when applied to pollutant transport to Chico, versus transport to Red Bluff or Redding. This was due to the likelihood of regular surface transport to Chico, versus the regular occurrence of a surface convergence zone in the Upper Sac (see Section 4) and the possibility of aloft transport to Redding and Red Bluff (see Section 9), which both made it difficult to properly estimate the transport path.

- Precursor contribution estimates for surface transport to Chico on 11 days in 1987 and 7 days in 1989 were quite consistent:

Area	Contribution to ROG and NOx (%)
Upper Sac	30-55
Broader Sac	30-40
SF Bay Area	15-25

  Precursor contribution estimates for 7 local days at Chico in 1987 were 100 percent from the Upper Sac; local days were defined as ones where the back trajectories had remained within about 75 km of Chico.

- Pollutant transport to Chico on August 5, 1989 was examined because this was the day with the highest ozone concentration and when we have both surface and aloft wind data, although the maximum ozone concentration was only 9 pphm. Precursor contribution estimates for this day were quite consistent, based on both surface and aloft trajectories:

Area	Contribution to ROG (%)	Contribution to NOx (%)
Upper Sac	60-70	65-85
Broader Sac	10-30	5-15
SF Bay Area	10-20	2-25

- Precursor contribution estimates for surface transport to Red Bluff on 10 days in 1987 were quite consistent:

Area	Contribution to ROG and NOx (%)
Upper Sac	55-70
Broader Sac	15-20
SF Bay Area	15-20

  Precursor contribution estimates for eight local days at Red Bluff in 1987 were 100 percent from the Upper Sac.

- Precursor contribution estimates for surface transport to Redding on 3 days in 1987 were 80 to 90 percent from the Upper Sac, with the rest from the Broader Sac and the SF Bay Area. Precursor contribution estimates for 15 local days at Redding in 1987 were more than 90 percent from the Upper Sac. However, all of these cases were based on surface trajectories; whereas aloft transport and/or carryover may have occurred and significantly modified the definition of local or transport and the relative contributions.

6.4 RECOMMENDATIONS

The following are recommendations for future work:

- Ozone exceedances at Redding often occur when there is a convergence zone in the Upper Sac and when there is the potential for nighttime transport aloft. A complete understanding of how these exceedances occur will require aloft meteorological measurements north of the convergence zone, preferably near Redding.

- In this study, upper-air meteorological data was critical for determining transport paths and estimating precursor contributions. This aloft data was obtained during special short-term field studies, but the data was not always available on ozone violation days or at the appropriate locations. Programs to obtain aloft meteorological and air quality data are critical for determining transport paths and estimating precursor contributions in the future.

- Ozone monitoring along potential transport paths is often critical to understanding when and by what route transport takes place. Ozone and nitrogen oxides monitoring should be performed at a few more sites between the Broader Sac and the Upper Sac besides at the receptor sites of Redding and Chico, especially on the west side of the Sacramento Valley; data at Red Bluff and either Arbuckle or Colusa would be very useful.

- Prepare simple relative ozone and nitrogen oxides flux estimates using data from additional monitoring sites along potential transport paths; install additional monitors at critical locations in order to prepare such estimates.

- Perform additional analyses of the August 7-8, 1990 ozone episode in the Sacramento Valley, including flux calculations, once the SACOG modeling is finished.

- Consider using an emissions-accumulation box which is narrower than 45 km at distances within about 50 km of the receptor area. This would reflect the narrower area of potential influence close to a receptor site. Decreasing the box width gradually from 45 to 5 km might be a reasonable choice.

- Prepare additional precursor contribution estimates using an emissions inventory with fewer biogenics and with no biogenics, as a bounding-estimate of the actual effect of biogenics on ozone concentrations. With the current biogenics inventory, the Upper Sac contributions remained high even when obvious transport occurred.